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# DEVELOPMENT OF A NONLINEAR "D" TYPE BOILER MODEL

Thomas Daniel Leclair Walker

# NAVAL POSTGRADUATE SCHOOL
Monterey, California

# THESIS

## DEVELOPMENT OF A NONLINEAR "D" TYPE BOILER MODEL

by

Thomas Daniel Leclair Walker

December 1979

Thesis Advisor: T. M. Houlihan

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# DEVELOPMENT OF A NONLINEAR "D" TYPE BOILER MODEL

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1979

# ABSTRACT

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# I. INTRODUCTION

Recent developments in control theory and practice coupled with digital electronics advances have produced increased interest in digital power plant modeling. Although conventional marine boiler modeling is not a new concept, it is still an area of increased interest due to the relative lack of analytical data. This deficiency is due primarily to the extreme environment that must be endured by sampling equipment. Advances in data collecting and processing equipment have made boiler data collection practically feasible, and in fact, nuclear steam generator development depends heavily on actual data. However, it is not economically feasible for a single manufacturer to retrofit modern data collection systems on a standard marine boiler. The majority of marine boiler models available are not attractive from the control engineer's viewpoint because of one or more of the following:

a. The model is over-simplified to the point of being a "teapot" model.

b. The model is completely developed and written in Laplace transforms and the state space equations are too difficult to extract.

c. The model is over-complicated to the point of being computationally inefficient.

d. The causes and modeling of "shrink and swell" phenomena are ignored.

This model attempts to compromise between simplification and complication while including a theory and model for shrink and swell. The model follows the path specified by Fini [1] restated below:

a. A general D-type marine boiler model is prepared in Continuous System Modeling Program (CSMP) language.

b. A general FORTRAN program is used to prepare the initial conditions needed by the CSMP model.

c. The initial condition program depends only on data easily obtained from the manufacturer's technical manual and engineering handbooks.

# II. MODEL CONSIDERATIONS

## A. BOILER TYPE

The D-type boiler was chosen for modeling because of its comparative standardization among manufacturers coupled with its popularity in naval ship power plants. This particular boiler is one installed in the LHA-1 class of United States naval ships. Since D-type boilers operate under a wide range of geometry and output conditions the initial condition and model programs are designed to operate over similar ranges.

## B. MODEL NOMENCLATURE

The model nomenclature differs from reference [1] because of a need to clarify the model equations and afford readability to the actual computer programs. The following objectives were considered when developing the nomenclature.

a. The equations must be easily read, necessitating minimum variable-definition referrals by the reader.

b. The notation used in the model development must be the same as that used in the computer programs.

The resulting notation combines a. and b. and consists of frequently used notations for variables followed by a subscript to indicate state point location and/or time using Figure 1.

Table 1, a tabulation of general rules and examples,

should suffice to allow the reader to follow the model development.

## C. EQUATION DEVELOPMENT FORMAT

The dynamic model and initial condition programs are developed simultaneously with corresponding equations written in appropriate proximity to each other. A notation of [IC] following an equation indicates that it is an initial condition equation, while a notation of [ME] indicates a model equation. In some instances the equation applies to both programs, an indication of [IC, ME] is used to indicate this.

In as many instances as possible equations are developed directly from elementary heat transfer and fluid dynamic principles. This stems from a desire to encourage more research in this particular field and to foster a better understanding of marine boiler dynamics among students of marine engineering. The model was developed to be read and used by students with a minimum of additional research.

## D. ASSUMPTIONS

Various assumptions are made to facilitate either model simplification or program tractability. The latter are not always desirable and further research or different programming techniques may obviate the need for them. The following major assumptions are made:

1. The energy transferred to the generating tubes is distributed uniformly, i.e. "even heating" exists.

2. There is a thorough mixing of the fluid in the steam drum.
3. Steam generation occurs only in the boiling section of the screen and main bank risers.
4. All generating tubes and downcomers in a particular circuit have the average geometry.

Uniform energy transfer is assumed to facilitate model simplification and is justifiable since the generating banks are designed to optimize uniform heat transfer. Mixing of the fluid in the drum is a result of the turbulence in the drum. The third assumption results from a lack of reliable experimental data and the knowledge that D-type boilers are natural circulation boilers relying on a density difference in the circulation loop to promote flow. Steam production outside of the generating banks would decrease the density difference, thus inhibiting natural circulation. The geometry assumption is necessitated by model simplification.

# III. MODEL DEVELOPMENT

## A. GENERAL

The boiler is developed from control volumes for which the appropriate equations for energy transfer and storage rates are written. The initial condition equations are generated by setting the rate (d/dt) terms equal to zero and solving for the desired variables.

The model is developed with three different elements:

1. Furnace-side heat transfer
2. Water-side heat transfer
3. Water-side circulation

## B. FURNACE-SIDE HEAT TRANSFER

The gas flow path can be followed on Figure 1 where it is represented by the dashed line. The fuel and air mixture enters the furnace at state point Q where radiation heat transfer occurs to the screen riser tube metal. The flue gas then leaves the furnace and exchanges heat via convection with the superheater (state point R-S), main bank riser tubes (state points S-T), and economizer (state points T-U) in that order.

At state point Q the fuel-to-air ratio and fuel and air temperatures are relatively constant. This allows the sensible heat of the fuel and air to be lumped. The mass flow rate into the furnace is the sum of the air flow and fuel flow.

$$\mathrm{MQQ} = \mathrm{MFQQ} + \mathrm{MAQQ} \qquad [\mathrm{ME}]$$

The initial values of fuel and air flow at a specified operating point are known. Therefore, the corresponding initial condition equation is:

$$\mathrm{MQQ0} = \mathrm{MFQQ0} + \mathrm{MAQQ0} \qquad [\mathrm{IC}]$$

The mass flow rates through the remaining sections of the boiler are the same.

$$\mathrm{MQQ} = \mathrm{MRR} = \mathrm{MSS} = \mathrm{MTT} = \mathrm{MUU} \qquad [\mathrm{ME}]$$
$$\mathrm{MQQ0} = \mathrm{MRR0} = \mathrm{MSS0} = \mathrm{MTT0} = \mathrm{MUU0} \qquad [\mathrm{IC}]$$

The total heat supplied to the boiler can be written as the product of the mass flow rate of fuel and the "lumped" fuel heating value.

$$\mathrm{QQ} = \mathrm{MFQQ} * \mathrm{FHV} \qquad [\mathrm{ME}]$$

At a specific operating point the heat released to the furnace is available from the technical manual as is the furnace volume. The total heat input at steady state is the product of these two.

$$\mathrm{QQ0} = \mathrm{QTOT0} * \mathrm{FURVOL} \qquad [\mathrm{IC}]$$

This allows the computation of the fuel heating value.

$$\mathrm{FHV} = \mathrm{QQ0} / \mathrm{MFQQ0} \qquad [\mathrm{IC}]$$

### 1. Furnace to Screen Risers

The heat transfer to the furnace screen tubes occurs primarily through radiation, i.e.

$$q = \sigma A \left( T_{RR}^{4} - T_{VV}^{4} \right)$$

which is the Stefan-Boltzmann law[1] where $\sigma$ is the Stefan-Boltzmann constant defined as:

$$\sigma = 2.8567 \times 10^{-11} \frac{\text{BTU}}{\text{sec}-\text{ft}^{2}-{}^{\circ}\text{R}^{4}}$$

Therefore the heat transfer to the furnace screen can be written

```
Q1 = SIGMAA * ((TRR+460.0) ** 4.0
     -(TVV + 460.0) ** 4.0)                [ME]
```

where

$$\text{SIGMAA} \equiv \sigma * A$$

At a given operating point, technical manual values are specified for the furnace heat absorption rate and the area of the radiant heat absorbing surface of the furnace screen. The product of these two yields the steady state heat transfer rate which in turn can be used to compute SIGMAA.

---

[1] This equation assumes that all the radiation from the combustion flame strikes the screen tubes, and both the flame and the tubes behave as black surfaces.

$$\mathrm{Q10} = \mathrm{QFURAB} * \mathrm{ARAD} \qquad [\mathrm{IC}]$$

$$\mathrm{SIGMAA} = \mathrm{Q10} / ((\mathrm{TRR0} + 460.0) ** 4.0 - (\mathrm{TW0} + 460.0) ** 4.0)$$

An energy balance equation for the mass of flue gases in the furnace region can be written in the form

$$\frac{d}{dt}(m\, c_p\, T) = \text{total energy supplied} - \text{energy transferred to screen tubes} - \text{energy of gas leaving furnace region}$$

or

$$\frac{d}{dt}(\mathrm{MASSQR} * \mathrm{CQR} * \mathrm{TRR}) = \mathrm{QQ} - \mathrm{Q1} - \mathrm{MRR} * \mathrm{CQR} * (\mathrm{TRR} - \mathrm{TAMB})$$

Note: TRR-TAMB is the absolute temperature. At steady state the rate terms are equal to zero. Values of total heat supplied to the boiler, heat transfer rate to the screen tubes, total flue gas flow rate, and flue gas temperature are available from previous equations. This allows the specific heat of the flue gas in the furnace region to be computed.

$$\mathrm{CQR} = (\mathrm{QQ0} - \mathrm{Q10}) / (\mathrm{MRR0} * (\mathrm{TQR0} - \mathrm{TAMB})) \qquad [\mathrm{IC}]$$

During a transient, the density of the flue gas in the furnace and the specific heat of the furnace flue gas can be regarded as constants near a steady state operating point. The dynamic equation can be written as

$$\mathrm{DTRR} = (\mathrm{QQ} - \mathrm{Q1} - \mathrm{MRR} * \mathrm{CQR} * (\mathrm{TRR} - \mathrm{TAMB})) / (\mathrm{MASSQR} * \mathrm{CQR}) \qquad [\mathrm{ME}]$$

where

$$\mathrm{MASSQR} = \mathrm{RFLUE} * \mathrm{FURVOL} \qquad [\mathrm{IC}]$$

Thus,

$$\mathrm{TRR} = \int_{t_1}^{t_2} \mathrm{DTRR} + \mathrm{TRR0}$$

or in CSMP-III language

$$\mathrm{TRR} = \mathrm{INTGRL}(\mathrm{TRR0}, \mathrm{DTRR}) \qquad [\mathrm{ME}]$$

The value for TRRO is available from the technical manual.

2. Flue Gas to Superheater

For the remaining tube banks heat transfer occurs primarily through convection. The energy given up by the flue gas in flowing over the tube surfaces is represented by the general equation

energy given up = mass flow rate of flue gas * specific heat of flue gas * change in temperature of the gas

i.e.

$$q = \dot{m} \, C_p \, \Delta T$$

At steady state, the energy transferred to the superheater tubes from the gas must equal the energy transferred from the tubes to the steam.

$$Q30 = Q40 \qquad [IC]$$

The steady state values for superheater inlet and outlet steam temperature and pressure are specified by the technical manual along with the superheated steam mass flow rate. This allows the direct computation of Q40 and Q30.

$$Q40 = MMM0 * (HNN0 - HMM0) \qquad [IC]$$

HMMO is the enthalpy of saturated steam corresponding to drum pressure, computed with curve fitted equations [2]. HNNO is available directly from the technical manual. The specific heat of the flue gas in the superheater region can now be computed.

$$CRS = Q30 / (MRR0 * (TRR0 - TSS0)) \qquad [IC]$$

Thus the dynamic equation for heat transferred from the flue gas to the tube metal is written:

$$Q3 = MRR * CRS * (TRR - TSS) \qquad [ME]$$

The heat transferred to the tubes via convection may also be represented by the Grimson correlation [3] which states that for cross flow over tubes;

$$\frac{hd}{k_f} = C\left(\frac{u_\infty d}{\nu_f}\right)^n Pr^{1/3}$$

where

$u_\infty$ = velocity
$d$ = tube diameter
$C$ = constant
$Pr$ = Prandtl number

Since h can also be written

$$h = q/A\Delta T$$

then

$$q = AC\left(\frac{u_\infty d}{\nu_f}\right)^n Pr^{1/3}\Delta T\left(\frac{k_f}{d}\right)$$

also

$$u_\infty = \frac{\dot{m}}{\rho A}$$

leading to the general equation

$$q = AC\left(\frac{d}{\nu_f \rho A}\right)^n Pr^{1/3}\dot{m}^n \Delta T\left(\frac{K_f}{d}\right)$$

Around a particular steady state operating point the physical properties can be regarded as a constant and the physical dimensions are constant, i.e.

$$AC \left( \frac{d}{\nu_f \rho A} \right)^n Pr^{1/3} = \text{constant}$$

which implies

$$q = (\text{constant}) * \dot{m}^n \Delta T$$

For flow over tube banks with differing rows of tubes and differing tube geometries the constant (n) varies little and the average is approximately .6 [3]. Therefore, in the case of the superheater and main bank riser tubes, the correlation is used in the form

$$q = C \dot{m}^{.6} \Delta T$$

or for the superheater

$$Q3 = KRS * MRR ** .6 * (TRS - TWW)$$

where TRS is the average flue gas temperature

$$TRS = (TRR + TSS) / 2.0$$

Since the steady state values for Q30, MRRO, TRRO, TSSO, and TWWO are given by the technical manual the constant KRS can be calculated.

$$KRS = Q30 / (MRR0 ** .6 * (TRS0 - TWW0)) \quad [IC]$$

To provide the dynamic solution of superheater flue gas outlet temperature, the two transient equations for the flue gas to superheater tube metal heat transfer are equated resulting in

$$\frac{TRS - TWW}{TRR - TSS} = MRR^{.4} * CRS / KRS$$

where

$$TRS = (TRR + TSS)/2.0$$

Solving the above for TSS gives

$$TSS = (TRR * (PHI1 - 1) + 2 * TWW)/(PHI1 + 1) \quad [ME]$$

where

$$PHI1 = 2 * MRR * * .4 * CRS/KRS \quad [ME]$$

### 3. Flue Gas to Main Bank Risers

The equations for the flue gas to tube metal energy transfer in the main bank are derived similarly. For the equation involving flue gas specific heat;

$$Q5 = MSS * CST * (TSS - TTT) \quad [ME]$$

The Grimson correlation equation for the main bank risers is

$$Q5 = KST * MSS * * 0.6 * (TST - TYY)$$

where

$$TST = (TSS + TTT)/2.0$$

By equating these two equations as was done with the superheater the flue gas temperature leaving the main bank can be written

$$TTT = (TSS * (PHI2-1)+2*TYY)/(PHI2+1) \quad [ME]$$

where

$$PHI2 = 2*MSS**0.4*CST/KST \quad [ME]$$

The steady state heat transfer is computed differently than that for the superheater. Since the steady state heat transfer to the screen bank has been computed, the energy transferred to the main bank is the difference between the total energy transferred and the desuperheater and screen bank energy transfer. At steady state the mass flow rate of steam out of the boiler is equal to the mass flow rate of feed in the boiler and the total energy transferred is the mass flow rate multiplied by the enthalpy change between the outgoing steam and incoming feedwater. Thus, the steady state energy transfer equation for the main bank is

$$Q60 = MMM0*(HMM0-HBB0)-Q20-Q990 \quad [IC]$$

Q990 is computed in the water side heat transfer section.

Since Q50 = Q60 at steady state the heat transfer coefficient KST and the specific heat CST can be computed.

$$KST = Q50/(MSS0**0.6*(TST0-TYY0)) \quad [IC]$$

$$CST = Q50/(MSS0*(TSS0-TTT0)) \quad [IC]$$

4. Flue Gas to Economizer

The economizer tubes differ from the generating and superheater tubes in that they are finned. A reasonable finned tube heat transfer correlation was developed by Weirmann, et al. [4]

$$j = \frac{h \, Pr^{2/3}}{C_p \, G_{max}}$$

$G_{max}$ ≡ maximum mass flow rate

$j$ ≡ correlation constant

$C_p$ ≡ specific heat of flue gas

Since $h = \frac{q}{A \Delta T}$ the above correlation can be written

$$q = \frac{j \, A \, \Delta T \, C_p \, G_{max}}{Pr^{2/3}}$$

$G_{max}$ is a function of mass flow rate into the tube bank and tube bank geometry. Similar to the case of the Grimson coefficient used for the superheater and main bank tubes the physical and geometric properties are considered constant leading to the use of the correlation in the form

$$q = C \dot{m} \Delta T$$

Therefore, for the economizer the equation is

$$Q7 = KTU * MTT * (TTU - TXX)$$

where

$$TTU = \frac{TTT + TUU}{2.0}$$

Paralleling the superheater and main bank, the heat transfer may also be written

$$Q7 = MTT * CTU * (TTT - TUU) \qquad [ME]$$

The steady state equation development follows that of the superheater and main bank sections and is not repeated here. The equations are:

$$Q80 = MAA0 * (HBB0 - HAA0) \qquad [IC]$$
$$Q70 = Q80 \qquad [IC]$$
$$CTU = Q70/(MTT0 * (TTT0 - TUU0)) \qquad [IC]$$
$$KTU = Q70/(MTT0 * (TTU0 - TXX0)) \qquad [IC]$$
$$TTU0 = (TTT0 + TUU0)/2.0 \qquad [IC]$$

Knowing the values for KTU and CTU developed by the initial condition program allows the solution of the flue gas outlet temperature in the transient analysis. Thus,

[ME] $TUU = (TTT * (PHI3 - 1.0) + 2.0 * TXX)/$
$(PHI3 + 1.0)$

[ME] $PHI3 = 2.0 * CTU/KTU$

### C. WATER SIDE HEAT TRANSFER

#### 1. Risers

The heat supplied to the riser banks is used both in the boiling and nonboiling length of the tube; however the assumption is made here that the heat transfer is all under fully developed flow boiling conditions. Since the nonboiling length of the risers is relatively small, little error is produced. For fully developed nucleate flow boiling, Levy [5] suggests the equation

$$Q = \frac{A \; P_{sat}^{4/3}}{1.782 \times 10^{6}} \; \Delta T_{sat}^{3} \quad \frac{BTU}{sec-ft^{2}}$$

By lumping the constant area and denominator the riser equations can be written in the forms

$$Q = C \ast PSAT^{4/3} \ast \Delta TSAT^{3}$$

Therefore, the two riser equations are

$$Q2 = KV \ast PSAT \ast\ast (4.0/3.0) \ast (TVV - TSAT) \ast\ast 3.0 \quad [ME]$$

and

$$Q6 = KY \ast PSAT \ast\ast (4.0/3.0) \ast (TYY - TSAT) \ast\ast 3.0 \quad [ME]$$

for the screen and main bank respectively. A simple energy balance on the tube metal yields the metal temperatures, i.e.,

$$mass \ast C_p \ast \frac{dT}{dt} = q_{in} - q_{out}$$

The equations for screen and main bank metal temperatures are:

```
DTVV = (Q1-Q2)/(MASSV * CPV)          [ME]
TVV  = INTGRL(TVV0, DTVV)             [ME]
DTYY = (Q5-Q6)/(MASSY * CPY)          [ME]
TYY  = INTGRL(TYY0, DTYY)             [ME]
```

The heat transfer coefficient KY can be computed directly from tube geometrical data available in the technical manual;

```
KY = AREAMB/1.782E 06                 [IC]
```

Since Q10 = Q20 at steady state, the dynamic equation for Q20 can be solved in a steady state situation for KV,

```
[IC]  KV= Q10/(PSAT** (4/3)* (TVV0-TSAT)**3.0)
```

Q60 was computed in Section III-B.3. This allows the calculation of the initial main bank riser tube metal temperature,

```
[IC]  TYY0=(Q60/(KY* PSAT**(4/3)))**(1/3)+TSAT
```

In the case of the screen risers, the initial tube metal temperature is available from the technical manual and the initial heat transfer rate has been previously calculated. This allows the calculation of the screen riser steamside heat transfer coefficient,

```
[IC]  KV =Q10/(PSAT **(4.0/3.0)* (TVV0-TSAT)**3.0)
```

2. Desuperheater

The Dittus-Boelter correlation [6] is used to compute the heat transfer rate from the steam to the desuperheater tubes. This correlation in its basic format is

$$Nu = .023\, Re^{0.8} Pr^{n}$$

where

Nu => Nusselt number

Re => Reynolds number

Pr => Prandtl number

n => .3 (for cooling fluid)

When the appropriate variables and constants are substituted for the dimensionless numbers, the Dittus-Boelter correlation can be written

$$Q = K\dot{m}^{.8}\,\Delta T$$

where the constant K is defined as:

$$K = .023 * \frac{\text{thermal conductivity}}{\text{tube diameter}} * \text{heat transfer area}$$

$$* \left(\frac{4}{\pi * \text{tube diameter} * \text{viscosity} * \text{nr of tubes}}\right)^{.8}$$

$$* \; Pr^{.3}$$

and ΔT is the log-mean-temperature difference (LMTD).

Thus, for the desuperheater, the equation is

```
Q9 = KNP * MNN ** .8 * LMTDNP
```

KNP can be computed directly. Thus,

```
KNP = ((.023 * THCONN)/DNP)*(4.0/(PI * DNP
      * VISCON * NTUBDS))** 0.8 * PRAN ** 0.3
      * AREADS                                   [IC]
```

The energy given up by the steam to the tubes may also be written in terms of steam specific heat, flow rate, and temperature difference.

```
Q9 = CNP * MNN * (TNN - TPP)                     [ME]
```

Similarly since the heat transfer to the water in the drum is totally by convection;

```
Q99 = KZ * (TZZ - THH)                           [ME]
```

For initial condition calculations THH is considered to be equal to TSAT. Therefore

```
KZ = Q990 / (TZZ0 - TSAT)                        [IC]
```

The desuperheater outlet temperature is solved by equating the two dynamic equations for Q9 and solving for the desired outlet temperature.

```
TPP = (TNN - TZZ)/(EXP(KNP/(CNP * MNN** 0.2)))
      + TZZ                                      [ME]
```

The instantaneous desuperheater tube metal temperature is obtained by an energy balance on the tube metal similar to that for the riser tube metal.

$$\text{mass} * C_p * \frac{dT}{dt} = q_{in} - q_{out}$$

Solving the appropriate equation for dT/dt results in

```
DTZZ = (Q9-Q99)/(MASSZ * CPZ)     [ME]
TZZ  = INTGRL (TZZ0, DTZZ         [ME]
```

The specific heat of the steam in the desuperheater (CNP) may be calculated using the known steady state values for desuperheated steam flow rate and the desuperheater inlet and outlet temperatures and pressures.

```
Q90 = MNN0 *(HNN0 - HPP0)        [IC]
CNP = Q90/(MNN0 *(TNN0 -TPP0))   [IC]
```

With the value of Q90 computed the initial log-mean-temperature difference can be calculated.

```
LMTDNP = Q90/(KNP *MNN0 ** 0.8)
```

The log-mean-temperature difference is a function of steam temperature in, tube metal temperature, and steam temperature out; therefore the initial tube metal temperature may be calculated.

```
TZZ0 = (TNN0-EXPODS*TPP0)/(1.0-EXPODS) [IC]
EXPODS = EXP((TNN0 - TPP0)/LMTONP)  [IC]
```

3. Economizer

Paralleling the desuperheater development the Dittus-Boelter correlation is used to relate the heat transfer from the tube metal to the feedwater. Thus,

$$Nu = .023 \, Re^{0.8} Pr^{n}$$

the only difference being that n is now .4 vice .3 because the fluid is now being heated. The appropriate constants are again lumped yielding

```
Q8 = KX * MAA ** 0.8 * LMTOAB
```

An energy balance on the water gives the heat absorbed in two other forms;

```
Q8 = MAA * (HBB - HAA)
Q8 = MAA * CAB * (TBB - TAA)      [ME]
```

At the specified operating point the inlet and outlet conditions of the economizer as well as the mass flow rate are given, allowing the computation of the steady state heat transfer.

```
Q80 = MAA0 * (HBB0 - HAA0)    [IC]
```

The heat transfer coefficient KX is computed directly.

```
KX = ((.023*THCONA)/DAB)*(4.0/(PI*DAB*
     VISCOA*NTUBEC))**0.8*PRAA**0.4
     *AREAEC                                    [IC]
```

This permits the solution of the steady state log-mean-temperature difference.

```
LMTDAB = Q80/(KX*MAA0**0.8)          [IC]
```

Following the identical path delineated for the desuperheater, the tube metal initial temperature can be computed.

```
TXX0 = (TAA0-TBB0*EXPOEC)/(1.0-EXPOEC) [IC]
EXPOEC = EXP((TBB0-TAA0)/LMTDAB        [IC]
```

An energy balance on the economizer tube metal yields its instantaneous temperature.

```
DTXX = (Q8-Q7)/(MASSX*CPX)     [ME]
TXX  = INTGRL(TXX0,DTXX)       [ME]
```

By equating the formulations for Q8 involving LMTD and specific heat, the economizer outlet temperature may be calculated.

```
TBB= (TAA-TXX)/(EXP(KX/(CAB*MAA**0.2)))
     + TXX                              [ME]
```

The specific heat of the feedwater in the economizer is calculated at steady state using the computed value of steady state heat transfer and the given mass flow rates and inlet and outlet temperatures.

```
CAB = Q80/(MAA0*(TBB0-TAA0))   [IC]
```

4. Superheater

The development of the superheater equations follows that of the desuperheater and economizer and for that reason the development will not be repeated. The equations are listed below.

```
Q4 = CMN*MMM*(TNN-TMM)   [ME]
Q40 = MMM0*(HNN0-HMM0)   [IC]
CMN = Q40/(MMM0*(TNN0-TMM0))  [IC]
```

The initial superheater log-mean-temperature difference is computed directly allowing the subsequent calculation of the tube-metal-to-steam heat transfer coefficient used in the Dittus-Boelter equation.

```
LMTDMN = (TNN0-TMM0)/(ALOG((TWW0-TMM0)/
         (TWW0-TNN0)))                    [IC]

KW = Q40/(MMM0**0.8*LMTDMN)   [IC]
```

An energy balance on the tube metal yields the instantaneous tube metal temperature, the initial tube metal temperature being available from the technical manual.

```
DTWW  = (Q3-Q4)/(MASSW*CPW)      [ME]
TWW   = INTGRL (TWW0, DTWW)      [ME]
```

The superheater outlet temperature can now be calculated.

```
TNN = (TMM-TWW)/(EXP (KW/(CMN*MNN**
        0.2))) +TWW                 [ME]
```

## D. WATER-SIDE CIRCULATION

### 1. General

The water/steam side circulation equations are by far the most difficult to visualize and codify. These equations must be accurate in order to predict phenomena such as shrink and swell while appropriate assumptions and simplifications must be made in order to make the equations tractable.

As can be seen in Figure 1, the feedwater enters the economizer at state point A, passes through the economizer to the steam drum where it becomes part of the water volume. The liquid leaves the drum via the downcomers, both main bank and screen at state points G and C respectively. The main bank downcomer delivers its liquid to the main bank risers via the water drum, and the main bank risers deliver the fluid to the steam separators. The flow through the screen risers is the same with the exception that there is no water drum in this circuit. The steam separators separate the majority of

the water from the steam leaving the drum at state point M and the majority of the steam from the water being discharged back into the drum liquid. The steam, with a negligible amount of water passes through the superheater via state point M-N. At the outlet of the superheater the steam leaving at path III is used for "main" steam; that leaving via path II travels to the desuperheater where it is cooled, then leaves via state point P and is used for auxiliary steam.

The water leaving the separators with a small amount of entrained vapor is mixed with the incoming feed water and forms a "foaming" vapor/liquid mass in the bottom half of the drum. The liquid from this mass leaves via the downcomers and is circulated through the loop.

### 2. Downcomer Pressure Drop

A closer look at the downcomer flow is necessary to justify assumptions that are made in the development of the pressure-drop equations.

Circulation ratio is defined as the ratio of the total weight of steam liberated to the drum [7]. For a 600 pound marine boiler this circulation ratio is on the order of 20:1 [7 and 8]. This implies that for every 21 pounds of liquid flowing down the downcomers, 20 pounds of it has already traveled up the riser and is at saturation temperature. Therefore, assuming the downcomers are perfectly insulated, it is reasonable to assume that the downcomer liquid is at or very near saturation temperature.

The momentum equation for the downcomers may be written:

pressure at top - pressure at bottom
= frictional loss - gravitational head
+ entrance loss + bend loss
+ exit loss + inertia force

The inertia force term may be considered negligible [9]. This is the quasistatic approximation which basically states that pressure waves move much more rapidly through the system than the important time constants. This is mathematically equivalent to the elimination of a large negative eigenvalue. This quasistatic approximation is only good for on-line transients and does not apply for extremely large discontinuities which would result in the boiler being taken out of operation, (e.g., a ruptured tube). Therefore the downcomer momentum equation can be written:

pressure at top - pressure at bottom
= (friction factor * downcomer length
÷ downcomer diameter + entrance factor
+ bend factor + exit factor)
* (downcomer mass flow rate)$^2$ ÷ (2 * (downcomer
cross sectional area)$^2$ * density of fluid
in downcomer * $g_c$) - density of fluid in
downcomer * gravitational acceleration *
height of downcomer ÷ $g_c$

In the model notation

$$\mathrm{PCPD} = (\mathrm{FCD} * \mathrm{LCD}/\mathrm{DCD} + \mathrm{ENTRCD} + \mathrm{BENDCD} + \mathrm{EXITCD}) * \mathrm{MCC} ** 2.0/(2.0 * \mathrm{ACD} ** 2.0 * \mathrm{RHOCD} * \mathrm{GC}) - \mathrm{RHOCD} * \mathrm{G} * \mathrm{ZCD}/\mathrm{GC}$$

$$\mathrm{PGPH} = (\mathrm{FGH} * \mathrm{LGH}/\mathrm{DGH} + \mathrm{ENTRGH} + \mathrm{BENDGH} + \mathrm{EXITGH}) * \mathrm{MGG} ** 2.0/(2.0 * \mathrm{AGH} ** 2.0 * \mathrm{RHOGH} * \mathrm{GC}) - \mathrm{RHOGH} * \mathrm{G} * \mathrm{ZGH}/\mathrm{GC}$$

for the screen and main bank downcomers respectively. FCD and FGH are friction factors of the form

$$f = 1/(1.74 - 2 \mathrm{LOG} (R/KS))$$

where R is the pipe radius and KS is the relative sand roughness [11].

$$\mathrm{FCD} = 1.0/(1.74 - 2.0 * \mathrm{ALOG10}(\mathrm{KSCD})) \quad [\mathrm{IC,ME}]$$

$$\mathrm{FGH} = 1.0/(1.74 - 2.0 * \mathrm{ALOG10}(\mathrm{KSGH})) \quad [\mathrm{IC,ME}]$$

### 3. Riser Pressure Drop

The momentum equation for the riser boiling section must take two phase flow effects into account because the flow in the boiling section is not homogeneous. Thus, there is a relative velocity between the liquid and vapor phases here. The steam separators are included in the riser length. However,

the effective length of the separators and thus the pressure drop are considered negligible because of a general lack of information concerning these items.

The pressure drop due to single phase or homogeneous flow in the nonboiling riser section can be written

$$\Delta P_{SPF} = \Delta P_{acceleration} + \Delta P_{friction} + \Delta P_{gravity}$$

$$\Delta P_{acceleration} = \frac{\dot{m}^2}{g_c \ast A^2} \ast \frac{(\rho_{out} - \rho_{in})}{\rho_{out} \ast \rho_{in}}$$

$$\Delta P_{friction} = \frac{4 \ast f \ast length \ast \dot{m}^2}{g_c \ast D \ast (\rho_{out} + \rho_{in}) \ast A^2}$$

$$\Delta P_{gravity} = \frac{g \ast height \ast (\rho_{out} + \rho_{in})}{2 \ast g_c}$$

Experiments conducted by Babcock and Wilcox [10] indicate that these homogeneous flow pressure drops may be modified to give the appropriate two phase flow pressure drops using correction factors that are functions of outlet quality and operating pressure. The two phase flow pressure drop can be written;

$$\begin{aligned} \Delta P_{TPF} = {} & \Delta P_{acceleration} \ast r_{acceleration} \\ & + \Delta P_{friction} \ast r_{friction} \\ & + \Delta P_{gravity} \ast r_{gravity} \end{aligned}$$

where the r terms are two phase flow correction factors available by using curve fits of the data from reference [10].

The form of these r terms become:

```
RGRAVE = 24.794 * XFF0 ** 2.0 - 6.5066 * XFF0 + .9776      [IC]
RGRAVK = 24.794 * XLL0 ** 2.0 - 6.5066 * XLL0 + .9776      [IC]

RACLE = 15.4564 * XFF0 ** 2.0 + 18.4944 * XFF0 - .00007    [IC]
RACLJ = 15.4564 * XLL0 ** 2.0 + 18.4944 * XLL0 - .00007    [IC]


RFRICE = -34.0822 * XFF0 ** 2.0 + 23.7164 * XFF0
         + .8734                                           [IC]

RFRICK = -34.0822 * XLL0 ** 2.0 + 23.7164 * XLL0           [IC]
         + .8734
```

Therefore, in the boiling region of the riser

$$\Delta P_{TPF} = \frac{\dot{m}^2 r_{acl}}{g_c \rho_{in} A^2} + \frac{2 f (\text{boiling length}) \dot{m}^2 r_{fric}}{g_c (\text{diameter}) \rho_{in} A^2} + \frac{g (\text{height of boiling region}) \rho_{in} r_{grav}}{g_c}$$

The total pressure drop across the length of the riser is;

$$\Delta P = \Delta P_{SPF} + \Delta P_{TPF}$$

In model notation the equations are

```
PDPF= (MDD**2.0*(RHOEE-RHODD))/(GC*RHOEE*
      RHODD*ADE**2.0) +(4.0*FDE*LDE
      *MDD**2.0)/(GC*DDE*(RHODD+
      RHOEE)*ADE**2.0)+(G*ZDE*(RHODD
      +RHOEE))/(GC*2.0)+(MDD**2.0*
      RACLE)/(GC*RHOEE*AEF**2.0) +
      (2.0*FEF*LEF*MDD**2.0*RFRICE)/
      (GC*DEF*RHOEE*AEF**2.0) +
      (G*ZEF*RHOEE*RGRAVE)/GC
```

```
PJPL =(MJJ**2.0*(RHOKK-RHOJJ))/GC*RHOKK*
      RHOJJ*AJK**2.0)+(4.0*FJK*MJJ**
      2.0*LJK)/(GC*DJK*(RHOJJ+RHOKK)*
      AJK**2.0+G*ZJK*(RHOJJ+RHOKK)/
      (GC*2.0) +(MJJ**2.0*RACLK)/
      (GC*RHOKK*AKL**2.0) +(2.0*
      FKL*LKL*MJJ**2.0*RFRICK)/
      (GC*DKL*RHOKK*AKL**2.0)+
      (G*ZKL*RHOKK*RGRAVK)/GC
```

The friction factors are in the same form as those for the downcomers

```
FDE = 1.0/(1.74 - 2.0 * ALOG10 (KSDE))      [IC]
FEF = 1.0/(1.74 - 2.0 * ALOG10 (KSEF))      [IC]
FJK = 1.0/(1.74 - 2.0 * ALOG10(KSJK))       [IC]
FKL = 1.0/(1.74 - 2.0 * ALOG10 (KSKL))      [IC]
```

At a specified steady state operating point the pressure drop across the downcomers must equal the pressure drop across the risers and the downcomer flow rate must equal the riser flow rate. Therefore by equating the appropriate pressure drop equations and solving the resultant relation for the flow rates, the initial flow rates may be computed as

```
MFF00 = ((RH0CD0 * G * ZCD - G * ZDE0 * ((RHODD0
          + RHOEE0)/2.0) - G * ZEF0 * RHOEE0 *
          RGRAVE) / ((FCD * LCD/DCD + ENTRCD +
          BENDCD + EXITCD)/(2.0 * ACD * * 2.0
          * RHOCO0) + ((RHOEE0 - RHODD0)/
          (RHOEE0 * RHODD0 * ADF * * 2.0)) +
          (4.0 * FDE * LDE0 * 2.0)/(2.0 * DDF
          * (RHOEE0 + RHODD0) * ADF * * 2.0) +
          RACLE/(RHOEE0 * ADF * * 2.0) + (4.0
          * FEF * LEF0 * RFRICE)/(2.0 * DDF
          * RHOEE0 * ADF * * 2.0))) * * 0.5      [IC]
```

```
MLL00= ((RHOGH0 *G * ZGH - G * ZJK0 * ((RHOJJ0
       +RHOKK0/2.0) - G * ZKL0 * RHOKK0 *
       RGRAVK)/(((FGH * LGH/DGH + ENTRGH +
       BENDGH + EXITGH)/(2.0 * AGH ** 2.0
       * RHOGH0 + (RHOKK0 - RHOJJ0)/
       (RHOKK0 * RHOJJ0 * AJL ** 2.0)) +
       (4.0 * FJK * LJK0 * 2.0)/(2.0 * DJL
       * (RHOKK0 + RHOJJ0) * AJL ** 2.0) +
       RACLJ/(RHOKK0 * AJL ** 2.0)+(4.0
       * FKL * LKL0 * RFRICK)/(2.0 * DJK
       * RHOKK0 * AJL ** 2.0))) ** 0.5      [IC]
```

4. Riser Continuity

The relationship between the riser inlet and outlet mass flow rates is written in terms of the continuity equation for one dimensional unsteady flow,

$$\sum_{cs} \rho \bar{V} \cdot \bar{A} = -\frac{d}{dt} \int_{cv} \rho \, d\forall$$

In model notation, this becomes

```
MLL = MJJ - DRHOJL * VOLJL          [ME]
MFF = MOD - DRHODF * VOLDF          [ME]
```

The numerical differentiation technique used by CSMP-III is highly suspect, as are other techniques. An "averaging" system is used in the actual dynamic model. In addition, the flow rate down the downcomer and into the riser is held constant for the open loop boiler model.

### 5. Riser Quality and Density

The average density in the risers must be solved for explicitly. Linearly varying quality along the riser tube length follows directly from the assumption of uniform heat flux along the riser tube length. The average density along the tube length is the sum of the total change in density and the density entering divided by the riser tube length [1]. Assuming the density varies only in the boiling length of the riser, the total change in density can be written;

$$\int_{\text{boiling length}} \rho(l)\,dl$$

The average density is

$$\rho_{\text{average}} = \frac{1}{L}\left[\int_{\substack{\text{boiling}\\ \text{length}}} \rho(l)\,dl + \rho_f * \text{nonboiling length}\right]$$

where $\rho_f$ = density of saturated water

$L$ = total tube length

Since $\rho(\ell)$ varies linearly from entering to exiting, $\rho(\ell)$ can be written in the form

$$\rho(l) = \frac{1}{V_f + \frac{X_{out}}{L_B}(l - L_{NB})V_{fg}} \qquad [1]$$

where $V_f$ = specific volume entering

$X_{out}$ = quality at riser outlet

$L_B$ = boiling length

$LN_B$ = nonboiling length

$V_{fg}$ = change in specific volume from saturated liquid to saturated vapor

The integral of the explicit equation for $\rho(\ell)$ may be solved after rearrangement to

$$\rho(\ell) = \frac{1}{\left(V_f - \dfrac{X_{out}\, LNB\, V_{fg}}{L_B}\right) + \dfrac{X_{out}}{L_B} V_{fg}\, \ell}$$

which is of the form $\dfrac{1}{a + b\ell}$

This yields the average density,

$$\rho_{av} = \frac{1}{L}\left[\frac{L_B}{X_{out}\, V_{fg}} \ln\left[\frac{X_{out}\, V_{fg}}{V_f} + 1\right] + \rho_f\, L_{NB}\right]$$

In model notation the formula is written

```
RHODF0 = (1.0/LDF)*(LEF0/((XFF0)*VFG)
         * ALOG(((XFF0)/VF)*VFG +1.0)
         +RHODD0 * LDE0)                        [IC,ME]

RHOJL0 = (1.0/LJL)*(LKL0/((XLL0)*VFG)*
          ALOG((XLL0*VFG)/VF +1.0)+RHOJJ0
          * LJK0                                [IC,ME]
```

To permit calculation of the quality term the energy balance on the liquid in the riser tubes is evaluated. Thus,

rate of change of riser energy = flow energy in - flow energy out

+ thermal energy in

$$\frac{d}{dt}(\rho h V) = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + q_{in}$$

If the enthalpy term is treated as the average enthalpy in the riser the equation may be written

$$\frac{d}{dt}\left(\rho\left(h_f + X_{out} * h_{fg}/2\right)V\right) = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + q_{in}$$

In model notation this is written in the form:

```
OHXLL = (MGG *(HJJ-HF - XLL * HFG/2.0) + Q6 -MLL
        * XLL * HFG/2.0)/(RHOJL * VOLKL)          [ME]

HXLL  = INTGRL(HXLL0, DHXLL)                      [ME]
XLL   = (HXLL - HF) * 2.0/HFG                     [ME]
OHXFF = (MCC * (HDD-HF-XFF * HFG/2.0)+Q2
        -MFF * XFF * HFG/2.0)/(RHODF * VOLEF)     [ME]
HXFF  = INTGRL(HXFF0, OHXFF)                      [ME]
XFF   = (HXFF - HF)* 2.0/HFG                      [ME]
```

The initial conditions, HXLLO and HXFFO are calculated in the initial condition program.

The steady state equations for quality are derived differently. The energy transfer rate to the riser liquid may be written in the form

$$\dot{Q} = \dot{m}\,\Delta h$$

where

$$\Delta h = h_{out} - h_{in}$$
$$= h_f + x_{out} h_{fg} - h_{in}$$

Solving for $X_{out}$ yields

$$x_{out} = (\dot{Q} + \dot{m}(h_f - h_{in}))/(\dot{m}\, h_{fg})$$

or

```
XFF0 =(Q10 + MFF0 * (HF - HDD0))/(MFF0 * HFG)   [IC]
XLL0 =(Q50 + MLL0 * (HF - HJJ0))/(MLL0 * HFG)   [IC]
```

6. Riser Boiling Boundary Location

The nonboiling length of riser tube is the product of the riser tube length and sensible to total heat ratio [1]

$$L_{NB} = L \; q_s / q_t$$

The sensible to total heat ratio may be expressed as the enthalpy change in raising the water to saturated conditions divided by the total enthalpy change, i.e.

$$\frac{q_s}{q_t} = \frac{h_f - h_{in}}{(h_f + x_{out} h_{fg}) - h_{in}}$$

The equations for nonboiling length are

```
LOE0 = LDF * AMAX1((HF-HDD0),0.0)/((HDD0
        + XFF0 * HFG) - HDD0)                [IC]
LJK0 = LJL * AMAX1((HF-HJJ0),0.0)/((HJJ0
        + XLL0 * HFG) - HJJ0)                [IC]
```

The Fortran function AMAX1 is used here because the above equations are used in an iterative loop in the initial condition program and there is a possibility during iterations of reaching a situation where the enthalpy entering is greater than saturation enthalpy. The final initial condition solution prevents this. The AMAX1 function is not used for the dynamic model. Thus,

LDE = LDF * (HF - HDD)/((HF +XFF * HFG)- HDD) [ME]

LJK = LJL * (HF - HJJ)/((HF +XLL * HFG)-HJJ) [ME]

The boiling volume is derived directly from the solution for the nonboiling length.

$$\text{boiling volume} = \text{total volume} * \frac{\text{boiling length}}{\text{total length}} \quad \text{Hence,}$$

VOLEF = VOLDF * LEF/LDF [ME]

VOLKL = VOLJL * LKL/LJL [ME]

### 7. Steam Drum Liquid Mass and Energy Balance

The rate of change of liquid mass within the drum is equal to the sum of the mass flow rates entering and leaving the drum. The liquid mass flowing into the drum is the saturated liquid from the risers, the liquid from steam condensation in the drum, and the incoming feedwater. The liquid leaving is that leaving via the downcomers. The dynamic model equation is

$$\begin{aligned}\mathrm{DDMASL} = {} & \mathrm{MLL} * (1.0 - \mathrm{XLL}) + \mathrm{MFF} * (1.0 - \mathrm{XFF}) \\ & + \mathrm{MCOND} + \mathrm{MBB} - \mathrm{MCC} - \mathrm{MGG} \qquad [\mathrm{ME}]\end{aligned}$$

The instantaneous mass of liquid in the drum is

$$\mathrm{DMASL} = \mathrm{INTGRL}(\mathrm{DMASL0}, \mathrm{DDMASL}) \qquad [\mathrm{ME}]$$

where

$$\mathrm{DMASL0} = (\mathrm{VOLDRM} * \mathrm{RODRML})/2.0 \qquad [\mathrm{IC}]$$

The drum energy balance is derived similarly, i.e.,

$$\begin{aligned}\mathrm{DDMOHL} = {} & \mathrm{MLL} * (1.0 - \mathrm{XLL}) * \mathrm{HF} + \mathrm{MFF} * (1.0 - \mathrm{XFF}) \\ & * \mathrm{HF} + \mathrm{MCOND} * \mathrm{HFG} + \mathrm{MBB} * \mathrm{HBB} - \mathrm{MCC} \\ & * \mathrm{HCC} - \mathrm{MGG} * \mathrm{HGG} \qquad [\mathrm{ME}]\end{aligned}$$

The instantaneous drum energy is

$$\mathrm{DMOHL} = \mathrm{INTGRL}(\mathrm{DMOHL0}, \mathrm{DMOHL}) \qquad [\mathrm{ME}]$$

The initial drum energy is the product of the initial drum liquid mass and initial drum enthalpy.

$$\mathrm{DMOHL0} = \mathrm{DMASL0} * \mathrm{HDRUM0} \qquad [\mathrm{IC}]$$

The initial drum liquid enthalpy is

$$\mathrm{DH} = \mathrm{DMOHL}/\mathrm{DMASL}$$

In the dynamic model, drum liquid enthalpy is considered the enthalpy of saturated liquid.

The steam condensation rate equation is based on the difference between the pressure and temperature of the steam and that of the liquid [12]

```
MCOND = 560.93 * (PMM/(TMM+460.0)**0.5
        -PSAT/(TSAT+460.0)**0.5)+.02568        [ME]
```

The water level in a marine boiler is generally considered in reference to a mid-drum zero, that is, a water level of plus one inch implies the water level is one inch above the drum centerline. For computational efficiency the assumption is made that for small changes in water level around the midpoint of the drum the water surface area remains constant. This allows a simplified level equation, i.e.,

```
LEVEL = (DMOV-VOLDRM/2.0)/(LSTMDM * DSTMDM)    [ME]
```

DMOV is the equation for the total volume of "liquid" in the drum. Recalling that a small percentage of steam leaving the separators is entrained in the liquid, the rate equation for "liquid" volume in the drum is

```
DDMOV = ((MFF+MLL-MBB)* VF +PCU * (MLL+MFF)
        * VV + MBB * VBB - (MCC +MGG)* VF
        +MCOND * VFG)                          [ME]
```

where DMDVO is the volume occupied at time zero which is half the drum volume.

### 8. Circulation System Initial Condition Iteration Procedure

The initial conditions for the circulation system are found by flow rate balancing in the downcomer-riser flow loops. An initial guess of flow rate is made using the assumed riser exit quality of .05 percent which is reasonable for this type of boiler [7]. Coupling this assumption with the assumption that the percent carryunder is zero, an initial approximation of the flow rate can be determined using the figures for initial heat transfer rate to the risers calculated in Section III-A. Hence,

$$\text{mass flow rate} = \frac{\text{heat transfer rate}}{\text{assumed quality} * \text{latent heat of vaporization}}$$

A first approximation of downcomer enthalpy for both banks can be calculated. This downcomer enthalpy is assumed to be the same for all downcomers. Using an energy balance on the liquid in the steam drum

```
MFF0  = Q10/(XASUME*HFG)                               [IC]
MLL0  = Q50/(XASUME*HFG)                               [IC]
HCO0  = ((MFF0+MLL0-MBB0)*HF+MBB0*HBB0)/
         (MFF0+MLL0)                                   [IC]

HGH0  = HCO0                                           [IC]
```

The screen riser inlet enthalpy is assumed to be equal to that of the screen downcomer; however the main bank fluid absorbs additional energy from the desuperheater located in that circuit. Therefore, the main bank riser inlet enthalpy

must be calculated separately. Thus,

$$HJJ0 = HGH0 + Q90/MHH0 \qquad [IC]$$

The downcomer density must be calculated for use in the pressure drop calculations. Hence,

$$VCD0 = ((MFF0 + MLL0 - MBB0) * VF + MBB0 * VBB0)/(MFF0 + MLL0) \qquad [IC]$$

$$RHOCO0 = 1.0/VCD0 \qquad [IC]$$

$$RHOGH0 = RHOCO0 \qquad [IC]$$

The riser outlet quality is calculated using the initial quality formulation previously developed. This computation is followed by the calculation of the riser non-boiling and boiling lengths.

The average density of the risers is calculated along with the two phase flow multiplication factors for use in the flow rate/pressure drop calculation.

An updated flow rate is now computed and compared with the first approximation. If it is within a specified error criteria calculation stops. If not the previous approximation is updated and the calculations continued with the new approximation.

Upon completion of the flow rate balancing the initial flow rates in the downcomer/riser loops are known along with the riser outlet quality.

The steady state drum specific volume and density are computed as

```
VORML0 = VCO0 + PCU * VV
RODRML = 1.0 /VORML0
```

The initial steam mass in the drum is then calculated as

```
OSTM0 = VOLORM * RHOV/2.0
```

9. Superheater Pressure Drop

All entrance, head, and exit losses are considered negligible in the superheater compared to the frictional pressure drop.

$$\Delta P = f \frac{L}{D} \frac{\dot{m}^2}{A^2 \rho_{average}}$$

By lumping the constants the pressure drop equation is

```
PMM-PNN = KON1 * MMM ** 2.0 /RHOMN0
```

The following definitions apply here:

```
KON3 = (PMM0+PNN0)/(RHOMM0+RHONN0)   [IC]
RHOMN0 = (RHOMM0 + RHONN0)/2.0
KON1 = ((PMM0 - PNN0)* RHOMN0)/MMM0 ** 2   [IC]
```

10. Steam Valve Equation

The flow through the steam valve is considered directly proportional to the outlet pressure and valve opening, i.e.,

$\dot{m} = C * P * (\text{Valve Opening})$

```
MMMIII = PNN * KON4 * VALVE     [ME]
```

The constant is computed in the initial condition program.

```
KON4 = MMMIII /(VALVE0 * PNN0)     [IC]
```

E. EQUATIONS OF STATE

The equations of state listed below are used in both the initial condition and dynamic programs. With the exception of the subcooled specific volume equation used for the feedwater entering the drum, they are reasonably accurate in the 300-1500 psi range. The subcooled specific volume equation is accurate in the 600-800 psi range.

```
PSAT = EXP((ALOG(HSAT)-4.46708)/.26452          [2]
TSAT = EXP((.22151 * ALOG(PSAT)+4.77123))       [2]
HSAT = EXP(0.26452 * ALOG(PSAT)+4.46708)        [2]
HFG  = 922.15-0.40516 * PSAT+1.717E-04
       * PSAT ** 2.0-4.219E-08 ** 3.0           [2]
RHOF = 63.8-0.01781 * TSAT+1.132E-05
       * TSAT ** 2.0-6.786E-08 * TSAT
       * * 3.0                                  [2]

VBB = .01600488-.0000020146 * TBB
      + 3.6511E-08 * TBB ** 2.0
      - 8.142E-11 * TBB ** 3.0 + 1.4081E-13
      * TBB ** 4.0 - 1.148E-16 * TBB ** 5.0
      + 8.034E-20 * TBB ** 6.0
```

# IV. RESULTS AND CONCLUSIONS

## A. GENERAL

A listing of the initial condition program and the dynamic boiler model program is given in Appendices A and B respectively. The initial condition program output data must be properly formatted for input to the CSMP-III dynamic model. In addition, because the dynamic model utilizes the liquid in the steam drum as a saturation state point from which all other state points are derived, two of the initial conditions must be modified to eliminate a discontinuity between the steady state program and the dynamic model. The equations involved and an explanation are given below.

```
DMASL0 = (VOLDRM * RHOCD0)/2.0            [IC]
DMDHL0 = DMASL0 * HDRUM0                  [IC]
DMDHL  = INTGRL(DMDHL0, DDMDHL)           [ME]
DMASL  = INTGRL(DMASL0, DDMASL)           [ME]
DH     = DMDHL/DMASL                      [ME]
```

As stated previously, the enthalpy of the liquid in the drum is considered saturation enthalpy. The dynamic model must begin with the rate of condensation in the drum (MCOND) as close to zero as possible. This is a natural steady state position - drum liquid and drum steam both at the same pressure and temperature. In order to insure this to be the case DMASLO and/or DMDHLO must be modified such that the initial

drum enthalpy (DH) very closely approximates the enthalpy of saturated liquid corresponding to the drum steam temperature and pressure (PMM and TMM). This is easily facilitated by the use of the CALL DEBUG statement in the dynamic program With this procedure:

1. The initial condition program is executed and the initial conditions formatted for CSMP-III use.
2. The dynamic model is executed for only a short run time, i.e. 5 seconds.
3. Observing the DEBUG output from the model, DMASLO and/or DMDHLO are modified such that PSAT and TSAT equal PMM and TMM.
4. The model is reexecuted for a short run to check. MCOND should be very small.
5. Since DH is implicitly related to PMM and TMM, the procedure may have to be repeated a few times. The objective is to force as many of the "DERIVATIVE" terms in the DEBUG output to comparatively small figures as possible.

The model as used operates satisfactorily with DMASLO = 8002.2 and DMDHLO = 3.96163E 06. This forces the initial MCOND term to .35949.

Because of the CSMP function DERIV used in the program, the model is extremely sensitive to integration time step. Numerical differentiation is not a desirable function to perform in a dynamic model; however attempts to explicitly differentiate the equations concerned failed. One solution

to the problem is to "smooth" the derivative function by averaging it over several timesteps. The model performed satisfactorily with a fixed-step integration procedure (Runge-Kutta), an integration time step of .04 seconds, and averaging the derivative over sixteen time steps.

## B. OPEN LOOP RESPONSE

The open loop response to a ten percent increase in throttle opening is shown in Figures 2-7. As expected, the response of the main bank circulation loop and screen bank circulation loop is different. This is in keeping with the different purposes of those two loops, steam generation and furnace screening respectively. The effect of the valve opening increase is barely noticeable in the screen circulation loop.

The swell effect is not noticeable. Further conversations with Mr. Paul Weitzel at Babcock and Wilcox indicate that the percentage of "carry under" is not a constant as it was treated in this program. One to two percent is a good starting estimate for steady state; however during a transient "carry under" mass flow rate is computed by subtracting the amount of steam leaving the boiler from the amount of steam produced. This should always be a positive number. The vapor that does not leave the boiler is "carried under." The following program will implement this "carry under":

Modify the section of the dynamic model titled "COMPUTE THE DRUM SPECIFIC VOLUME" to read:

```
          PROCEDURE CRYUND=FILTR8(MMM)
          IF(TIME.GT.0.0)GO TO 45
          CRYUND=PCU*(MLL+MFF)
          GO TO 46
45        CRYUND=(MLL*XLL+MFF*XFF)-MMM
46        RISE1=DELAY (250,RISTIM,CRYUND)
          RISE2=CRYUND
          IF(VALUE.GT..51)GO TO 55
          RISE=RISE2
          GO TO 57
55        RISE=RISE1
57        CONTINUE
          ENDPROCEDURE
          DDMDV=((MFF+MLL-MBB)*VF+CRYUND*VV...
                +MBB0*VBB-(MCC+MGG)*VF+MCOND...
                *VFG-RISE*VV)
```

Follow the above statements with the unmodified equations for DMDV.

The previous procedure was not implemented in the present dynamic model. The quality formulation in the present model is apparently too simplified and this causes a shortfall in quality at the outlet of the screen riser bank. As a result of this shortfall, there are instances during transient operation when the model is not "producing" as much steam as it is "using". Mr. Weitzel suggests using twenty node finite difference approximation for quality. This could be done using an equation for quality such as:

$$X = \frac{q}{A \rho_f V_{in} h_{fg}} z$$

where

X = quality

Z = distance up the riser (ft)

$q$ = heat input to riser (BTU/s-ft)

$A$ = cross sectional area of riser ($ft^2$)

$\rho_f$ = density of saturated liquid ($lbm/ft^3$)

$V_{in}$ = velocity of liquid entering (ft/s)

$h_{fg}$ = latent heat of vaporization (BTU/lbm)

Simultaneously an implicit equation for continuity could be applied to produce a balanced mass flow rate without assuming that the downcomer mass flow rate remains constant.

## C. CONCLUSIONS

The model presented is not a finished model. Further research is needed to successfully implement the shrink and swell theories presented. When the previously mentioned difficulty with riser outlet quality is solved, the model should approximate the dynamics of a wide range of D-type marine boilers depending on the initial conditions supplied to the initial condition program.

The initial condition program develops the initial conditions necessary for the detailed boiler model with the relatively scant data available from the boiler technical manual shown in Appendix C and a small amount of data from common engineering handbooks. Because of the relatively small amount of data required the initial condition program and/or the model can serve as a basis for a boiler condition monitoring system.

## D. SUGGESTIONS FOR FURTHER RESEARCH

It is evident that the model suffers by using the CSMP-III function DERIV. In order to facilitate the explicit solution of the continuity equation for the riser banks some form of differentiation is required, either numerical or explicit. An explicit solution is much more desirable from a stability standpoint. A more detailed investigation with fewer assumptions might produce the correct form for the explicit differentiation equation. It should be noted, however, that when using explicit differentiation the model must average the derivative over at least two time steps to avoid the creation of an algebraic loop. This is easily done with the same PROCEDURE format used to average the derivative in the current model.

The use of small perturbation techniques to linearize the model and thus allow a state-space representation for multivariable control development and analysis should be undertaken. There is a computer code available locally to facilitate this for CSMP models; however it does not accept the CSMP DERIV function and/or the averaging procedure. A means of bypassing this problem would result in a general D-type boiler model - applicable to a very wide range of boilers currently in use - which could be linearized about specific operating points. These individual models could then be used for the development and testing of multivariable control systems.

Using locally available optimizing computer codes, an optimal D-type boiler design could be attempted with regards to boiler geometry.

A more detailed analytical and experimental investigation of current D-type marine boilers should be undertaken locally. Little research has been done in this area and that which has been done has often been based on either an incorrect physical model of a marine boiler or on a nuclear steam generating plant. A starting point could be the data analysis of common horizontal and vertical steam separators followed by an optimum design for these elements. The improper and/or maintenance of drum internals apparently grossly affects boiler operation and water level stability during rapid transients.

## TABLE 1
## MODEL NOTATION

| PRINCIPAL LETTER OR ACRONYM | MEANING | EXAMPLES |
|---|---|---|
| T | TEMPERATURE | TAA - temperature of fluid entering the economizer<br>TAB - average temperature of fluid in the economizer<br>TAAO - initial temperature of fluid entering the economizer |
| H | ENTHALPY | HDD - enthalpy of liquid entering the screen riser<br>HDDO - enthalpy of liquid entering the screen riser at time zero |
| V | SPECIFIC VOLUME | VBB - specific volume of liquid at economizer outlet |
| X | QUALITY | XFF - quality at outlet of screen risers<br>XLL - quality at outlet of main bank risers<br>DXFF - time rate of change screen riser outlet quality |
| RHO | DENSITY | RHODD - density at outlet of screen downcomer<br>RHOCD - average density in screen downcomer |
| M | MASS FLOW RATE | MGG - mass flow rate down main bank downcomer<br>MRRO - mass flow rate of flue goas through the superheater at time zero |
| Q | ENERGY TRANSFER | Q1 - energy transfer from furnace flue gas to screen riser tube metal<br>Q2 - energy transfer from screen riser tube metal to screen riser fluid |

NOTE: In general, rate variables $\frac{d}{dt}$ are preceded by the letter D, i.e., DHXFF, DRHOJL.

SCHEMATIC DIAGRAM OF A NAVAL BOILER

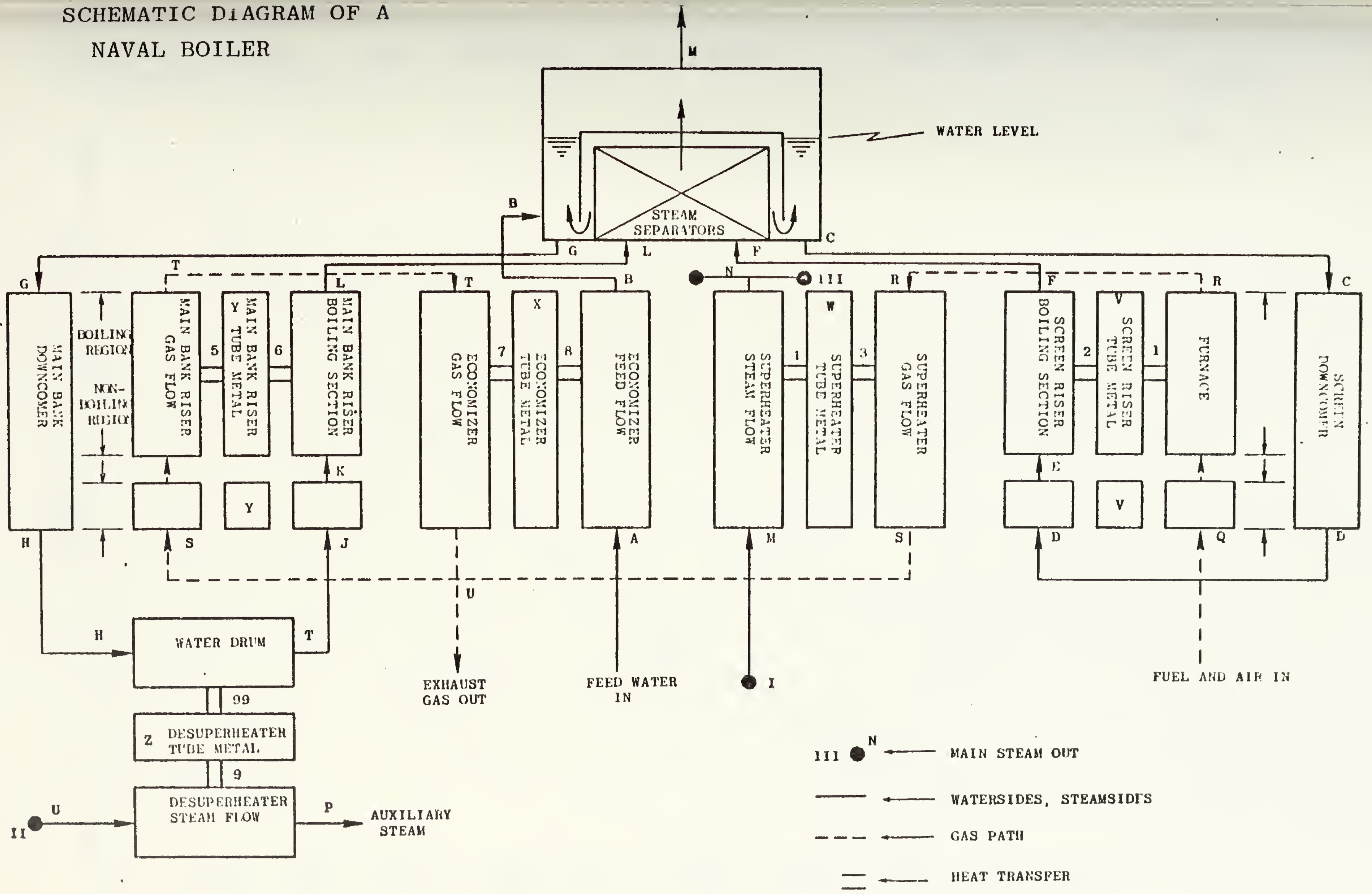

Figure 1.

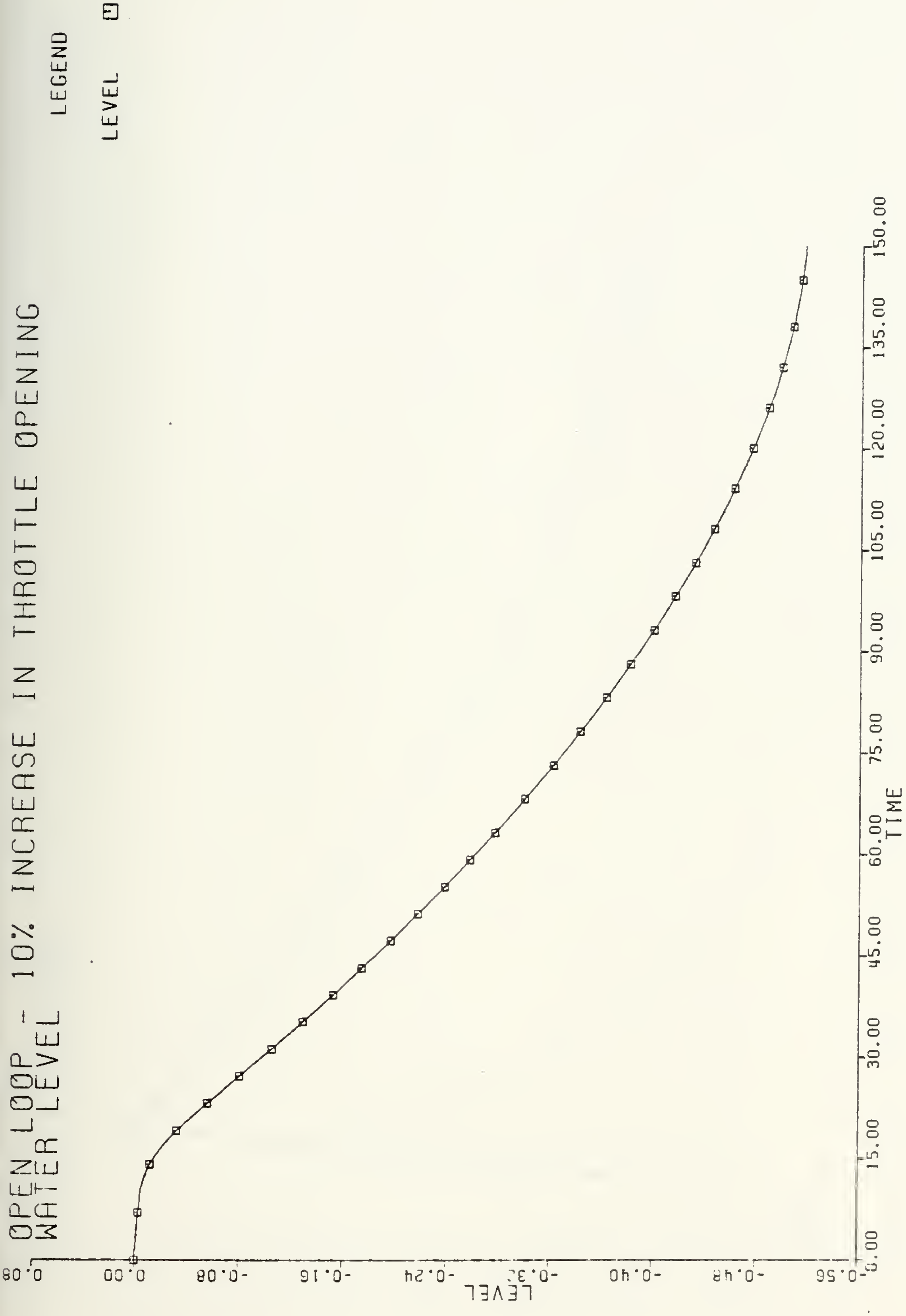
ØPEN LØØP - 10% INCREASE IN THRØTTLE ØPENING
WATER LEVEL
LEGEND
LEVEL ⊡
0.08
0.00
-0.08
-0.16
-0.24
-0.32
-0.40
-0.48
-0.56
LEVEL
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
TIME

Figure 2.

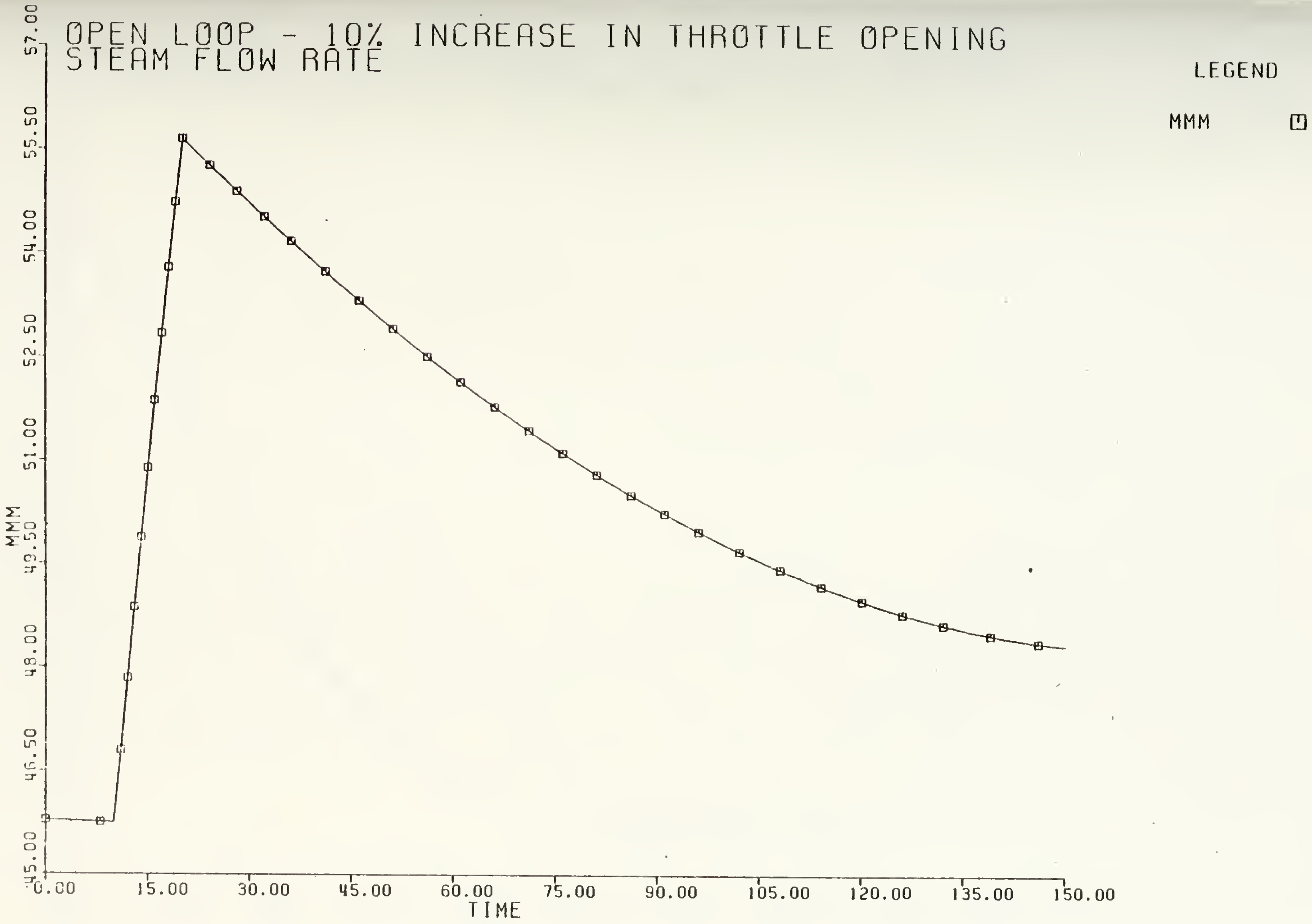
OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
STEAM FLOW RATE
LEGEND
MMM
MMM
TIME
45.00
46.50
48.00
49.50
51.00
52.50
54.00
55.50
57.00
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00

Figure 3.

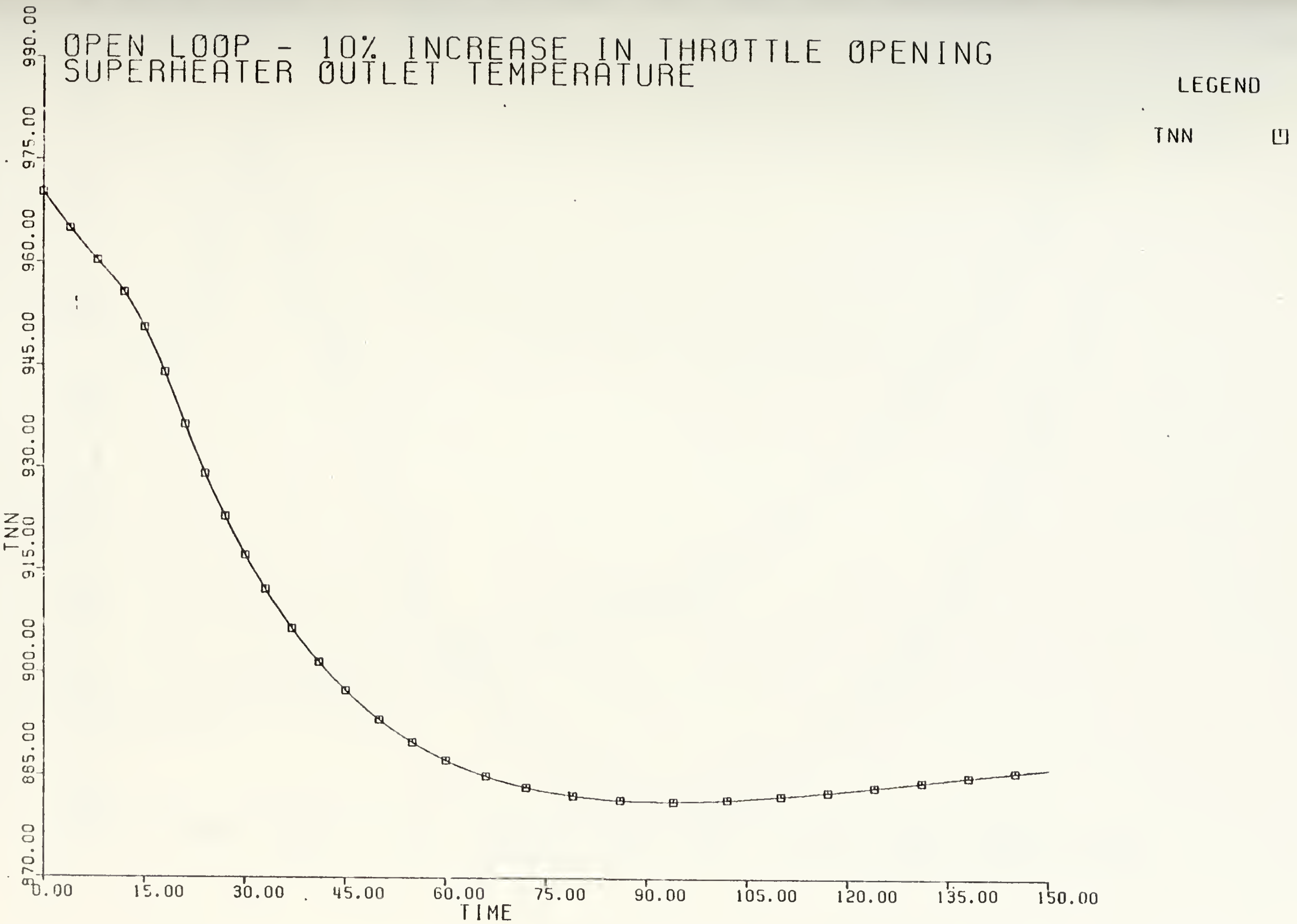
OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
SUPERHEATER OUTLET TEMPERATURE
LEGEND
TNN
TNN
990.00
975.00
960.00
945.00
930.00
915.00
900.00
885.00
870.00
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
TIME

Figure 4.

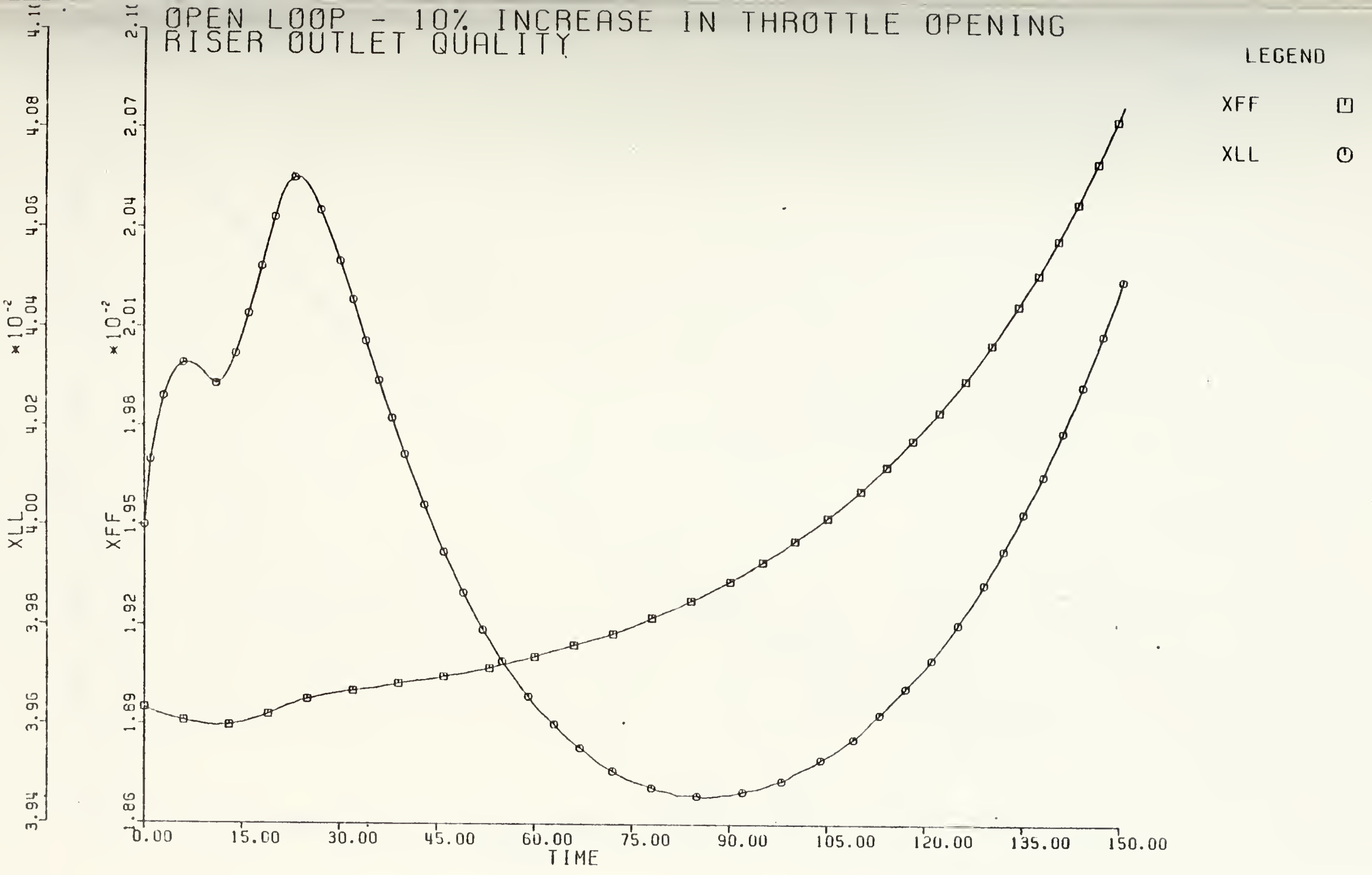
OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
RISER OUTLET QUALITY
LEGEND
XFF
XLL
XLL
$\times 10^{-2}$
3.94
3.96
3.98
4.00
4.02
4.04
4.06
4.08
4.1
XFF
$\times 10^{-2}$
1.86
1.89
1.92
1.95
1.98
2.01
2.04
2.07
2.1
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
TIME

Figure 5.

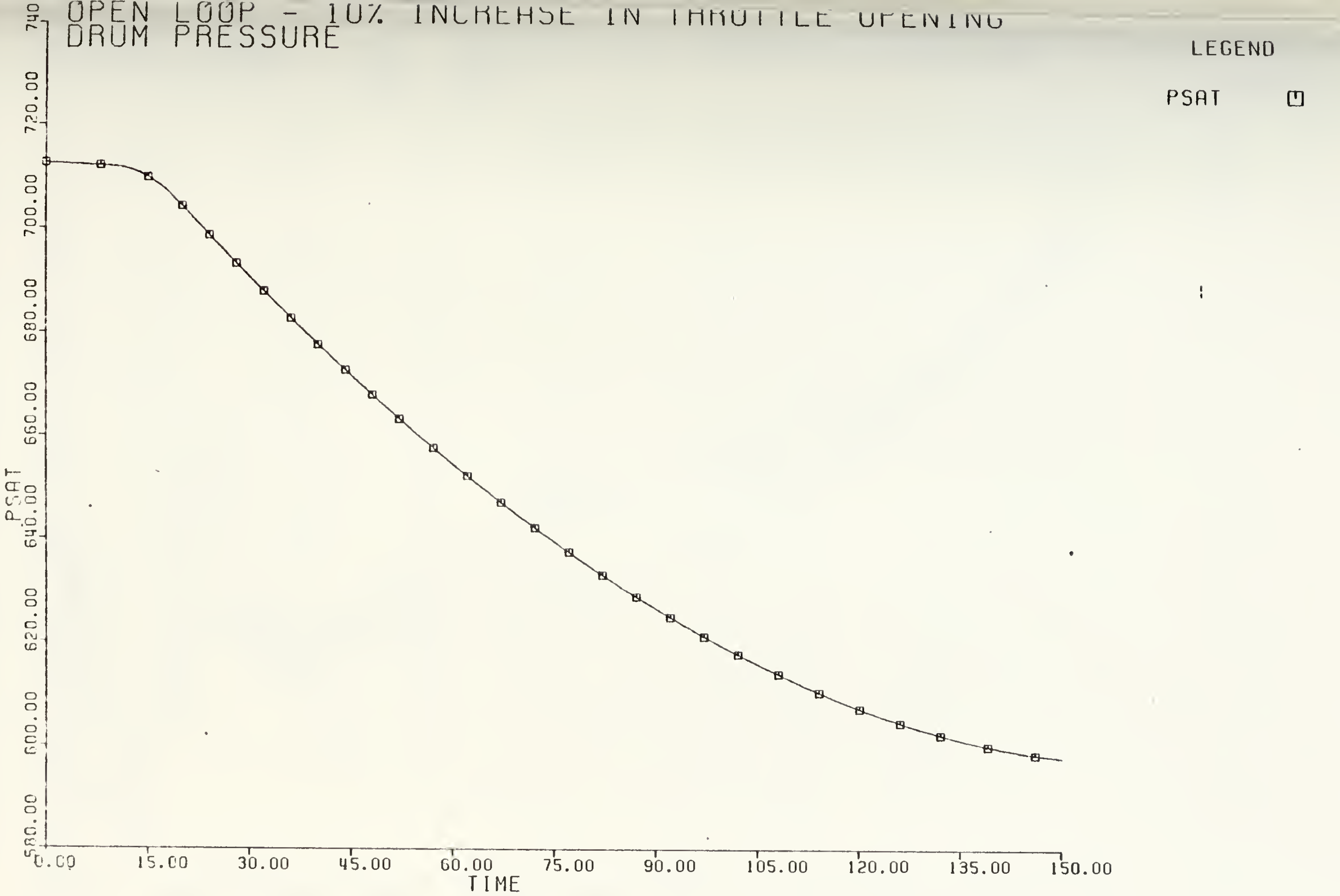
OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
DRUM PRESSURE
LEGEND
PSAT
PSAT
740
720.00
700.00
680.00
660.00
640.00
620.00
600.00
580.00
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00
TIME

Figure 6.

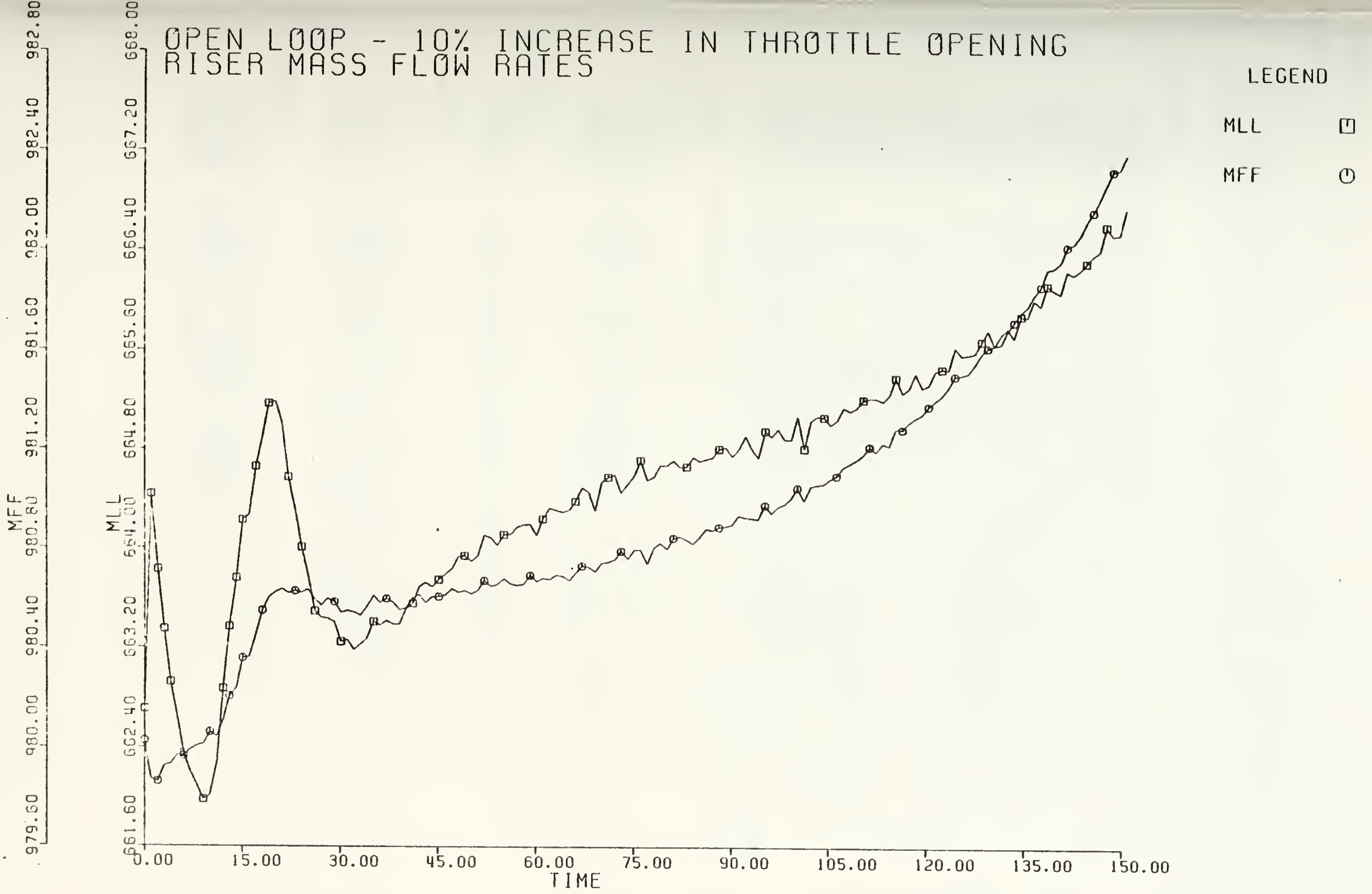
OPEN LOOP - 10% INCREASE IN THROTTLE OPENING
RISER MASS FLOW RATES
LEGEND
MLL □
MFF ○
MFF
982.80
982.40
982.00
981.60
981.20
980.80
980.40
980.00
979.60
MLL
668.00
667.20
666.40
665.60
664.80
664.00
663.20
662.40
661.60
TIME
0.00
15.00
30.00
45.00
60.00
75.00
90.00
105.00
120.00
135.00
150.00

Figure 7.

# APPENDIX A

```
08/30/79  20.55.11

ILE: CONSTANT FORTRAN  A1                          NAVAL POSTGRADUATE SCHOOL

     THIS PROGRAM CALCULATES THE CONSTANTS AND INITIAL CONDITIONS
     FOR A US NAVY D-TYPE BOILER GIVEN THE INPUT DATA OBTAINED FROM
     THE BOILER TECHNICAL MANUAL, STEAM TABLES, AND STANDARD ENGINEER-
     ING HANDBOOKS.  THE INPUT DATA ARE ENTERED IN NAME LIST FORMAT.
     NAMELIST DESIGNATIONS AND INPUT NEMONICS FOLLOW


     INCON1:

        OPPNT   OPERATING POINT(PERCENT)   *
        TOTSTM  TOTAL STEAM FLOW(LB/HR)
        SPHSTM  SUPERHEATER STEAM FLOW  (LB/HR)
        DSHSTM  DESUPERHEATED STEAM FLOW  (LB/HR)
        PDRUM   DRUM PRESSURE (PSIG)
        SHOT    SUPERHEATER OUTLET TEMPERATURE (DEG-F)
        SHOP    SUPERHEATER OUTLET PRESSURE (PSIG)
        DSHOT   DESUPERHEATER OUTLET TEMPERATURE (DEG-F)
        DSHOP   DESUPERHEATER OUTLET PRESSURE  (PSIG)
        ECONIT  ECONOMIZER FEED INLET TEMPERATURE (DEG-F)
        ECONOT  ECONOMIZER FEED OUTLET TEMPERATURE (DEG-F)
        AIRTMP  AIR INLET TEMPERATURE TO REGISTERS (DEG-F)
        OILTMP  OIL TEMPERATURE AT BURNER INLET (DEG-F)
        AIRFLO  AIRFLOW RATE (LB/HR)
        OILFLO  OIL FLOW RATE (LB/HR)
        XCSAIR  EXCESS AIR (PERCENT)  *
        DRAFT   DRAFT LOSS (IN-H2O)
        TGASSC  FLUE GAS TEMPERATURE LEAVING SCREEN (DEG-F)
        TGASSH  FLUE GAS TEMPERATURE LEAVING SUPERHEATER (DEG-F)
        TGASMB  FLUE GAS TEMPERATURE LEAVING MAIN BANK (DEG-F)
        TGASEC  FLUE GAS TEMPERATURE LEAVING ECONOMIZER  (DEG-F)
        TSCRN   SCREEN TUBE WALL TEMPERATURE (DEG-F)
        TSPHTR  SUPERHEATER TUBE WALL TEMPERATURE (DEG-F)
        HRFVOL  HEAT RELEASE (KBTU/HR/CU FT FURNACE VOLUME)
        FHAS    FURNACE HEAT ABSORBTION (KBTU/HR/SQ FT RADIANT HEAT
                ABSORBING AREA)

        NOTE: "PERCENT" VALUES ARE TO BE LOGGED AS DECIMALS.

     $SCREEN

        DTUBSC  AVERAGE INSIDE DIAMETER OF SCREEN TUBES (IN)
        LAVSC   AVERAGE LENGTH OF SCREEN TUBE (FT)
        NTUBSC  NUMBER OF SCREEN TUBES
        RHASSC  RADIANT HEAT ABSORBING AREA OF FURNACE SCREEN (SQ FT)
        MASSSC  TOTAL WEIGHT OF SCREEN TUBES (LB)


     $SPHTR

        AREASH  TOTAL SUPERHEATER HEAT TRANSFER AREA (SQ FT)
        MASSSH  TOTAL WEIGHT OF SUPERHEATER TUBES


     $MNBANK


        DTUBMB  AVERAGE INSIDE DIAMETER OF MAIN BANK TUBES (IN)
        LAVMB   AVERAGE LENGTH OF MAIN BANK TUBE (IN)
        NTUBMB  NUMBER OG MAIN BANK TUBES
        MASSMB  TOTAL WEIGHT OG MAIN BANK TUBES (LB)
        AREAMB  TOTAL HEAT TRANSFER AREA (SQ FT)


     $ECON

        DTUBEC  INSIDE DIAMETER OF ECONOMIZER TUBES(IN)
        NPASSE  NUMBER OF  TUBE PASSES
        NTUBEC  NUMBER OF TUBES PER PASS
        LTUBEC  AVERAGE LENGTH OF ECONOMIZER TUBE (FT)
        MASSEC  TOTAL WEIGHT OF ECONOMIZER (LB)
```

```
C
C
C       $DESPH
C
C          DTUBDS   INSIDE DIAMETER OF DESUPERHEATER TUBE (IN)
C          NTUBDS   NUMBER OF DESUPERHEATER TUBES PER PASS
C          NPASSD   NUMBER OF DESUPERHEATER TUBE PASSES
C          LTUBDS   LENGTH OF DESUPERHEATER TUBE (FT)
C          AREADS   TOTAL HEAT TRANSFER AREA OF DESUPERHEATER (SQ FT)
C          MASSDS   TOTAL WEIGHT OF DESUPERHEATER ASSEMBLY (LB)
C
C
C       $DRMDCR
C
C          DTUBDD   AVERAGE DIAMETER OF DRUM DOWNCOMER TUBES (IN)
C          LAVDD    AVERAGE LENGTH OF DRUM DOWNCOMER TUBE (FT)
C          NTUBDD   NUMBER OF DRUM DOWNCOMER TUBES
C
C
C       $HDRDCR
C
C          DTUBHD   AVERAGE INSIDE DIAMETER OF HEADER DOWNCOMER (IN)
C          LAVHD    AVERAGE LENGTH OF HEADER DOWNCOMER (FT)
C          NTUBHD   NUMBER OF HEADER DOWNCOMERS
C
C
C       $BOILER
C
C          DSTMDM   DIAMETER OF STEAM DRUM (IN)
C          LSTMDM   LENGTH OF STEAM DRUM (FT)
C          DWTRDM   DIAMETER OF WATER DRUM (IN)
C          LWTRDM   LENGTH OF WATER DRUM (FT)
C          HNORM    HEIGHT OF NORMAL WATER LEVEL ABOVE BENCH MARK (FT)
C          HHDR     HEIGHT OF HEADER (SCREEN) ABOVE BENCH MARK (FT)
C          HWTRDM   HEIGHT OF WATER DRUM ABOVE BENCH MARK (FT)
C          FURVOL   FURNACE VOLUME (CU FT)
C
C          NOTE:  CHOICE OF BENCH MARK IS ARBITRARY
C
C       $THERMO
C
C          HSHOUT   ECONOMIZER OUTLET ENTHALPY (BTU/LBM)
C          HDSOUT   DESUPERHEATER OUTLET ENTHALPY (BTU/LBM)
C          HECIN    ENTHALPY OF ECONOMIZER FEED INLET (BTU/LBM)
C          HECOUT   ENTHALPY OF ECONOMIZER FEED OUTLET (BTU/LBM)
C       (1)KH2O     THERMAL CONDUCTIVITY OF WATER  (BTU/HR.FT.DEG-F)
C       (1)PRH2O    PRANDTL NUMBER FOR WATER
C       (1)VSCH2O   KINEMATIC VISCOSITY FOR WATER (LBM/FT-SEC)
C       (2)KSTM     THERMAL CONDUCTIVITY FOR STEAM (BTU/HR.FT.DEG-F)
C       (2)PRSTM    PRANDTL NUMBER FOR STEAM
C       (2)VSCSTM   KINEMATIC VISCOSITY FOR STEAM (LBM/FT-SEC)
C          RSHOUT   SUPERHEATER OUTLET DENSITY (LBM/CU FT)
C          RDSOUT   DESUPERHEATER OUTLET DENSITY (LBM/CU FT)
C          RFLUE    DENSITY OF FLUE GAS AT TGASSC (LBM/CU FT)
C
C          NOTES:   (1) EVALUATED AT AVERAGE ECONOMIZER WATER TEMPERATURE
C                   (2) EVALUATED AT AVERAGE DESUPERHEATER STEAM TEMPERATUR
C
C       $LOSSES
C          KSDSC    ROUGHNESS RATION (SAND EQUIVALENT) FOR SCREEN TUBES
C          KSDMB    ROUGHNESS RATIO (SAND EQUIVALENT) OF MAIN BANK TUBE
C          KSDDD    ROUGHNESS RATIO (SAND EQUIVALENT) FOR DRUM DOWNCOMER
C          KSDHD    ROUGHNESS RATIO (SAND EQUIVALENT) FOR HEADER DOWNCOMER
C          ENTSC    SCREEN TUBE ENTRANCE LOSS
C          BENDSC    SCREEN TUBE BEND LOSS
C          ENTMB    MAIN BANK ENTRANCE LOSS
C          BENDMB   MAIN BANK BEND LOSS FACTOR
C          ENTDD    DRUM DOWNCOMER ENTRANCE LOSS FACTOR
C          BENDDD   DRUM DOWNCOMER BEND LOSS FACTOR
C          ENTHD    HEADER DOWNCOMER ENTRANCE LOSS FACTOR
```

```
C          BENDHD  HEADER DOWNCOMER BEND LOSS FACTOR                    CON01410
C                                                                        CON01420
      IMPLICIT REAL(A-Z)                                                 CON01430
      INTEGER NPASSE                                                     CON01440
      DIMENSION TH2O(20),QPASS(20)                                       CON01450
C                                                                        CON01460
C     DEFINE NAMELISTS                                                   CON01470
C                                                                        CON01480
      NAMELIST/INCON0/CFPNT,TOTSTM,SPHSTM,DSHSTM,PDRUM,SHOT,SHOP,DSHOT,  CON01490
     1DSHOP,ECONIT,ECONDT,AIRTMP,OILFLO,AIRFLO,XCSAIR,DRAFT,TGASSC,      CON01500
     2TGASSH,TGASMB,TGASEC,TSCRN,TSPHTR,HPFVOL,FHAS,OILTMP               CON01510
      NAMELIST/SCREEN/DTUBSC,LAVSC,NTUBSC,FHASSC,MASSSC                  CON01520
      NAMELIST/SPHTR/AREASH,MASSSH                                       CON01530
      NAMELIST/MNBANK/DTUBMB,LAVMB,NTUBMB,MASSMB,AREAMB                  CON01540
      NAMELIST/ECON/DTUBEC,NPASSE,NTUBEC,LTUBEC,MASSEC                   CON01550
      NAMELIST/DESPH/DTUBDS,NTUBDS,NPASSD,LTUBDS,AREADS,MASSDS           CON01560
      NAMELIST/DRMDCR/LTUBCD,LAVCD,NTUBCD                                CON01570
      NAMELIST/HDRDCR/DTUBHD,LAVHD,NTUBHD                                CON01580
      NAMELIST/BOILER/DSTMDM,LSTMDM,DWTRDM,LWTRDM,HNORM,HHDR,HWTRDM,     CON01590
     $FURVOL                                                             CON01600
      NAMELIST/THERMO/HSHOUT,HDSOUT,HECIN,HECOUT,                        CON01610
     1KH2O,PRH2O,VSCH2O,KSTM,PRSTM,VSCSTM,RSHOUT,RDSOUT,RFLUE            CON01620
      NAMELIST/LOSSES/KSDSC,KSDMB,KSDDD,KSDHD,ENTSC,BENDSC,ENTMB,        CON01630
     $BENDMB,ENTDD,BENDDD,ENTHD,BENDHD                                   CON01640
      NAMELIST/INCON1/TRRO,TVVO,TWWO,                                    CON01650
     &TYYO,TZZO,TXXO,TAAO                                                CON01660
      NAMELIST/INCON2/MAAO,MFQQO,MAQQO,                                  CON01670
     &MNNO,MMMO,MOQO,                                                    CON01680
     &MCDO,MGHO,MBBO,                                                    CON01690
     &MFFO,MLLO,MME,                                                     CON01700
     &MASSV,MASSW,MASSY,                                                 CON01710
     &MASSX,MASSZ,MASSQR,                                                CON01720
     &DMDHLO,DMASLO,DSTMO,CSTMDM,                                        CON01730
     &LSTMDM,DSTMDM                                                      CON01740
      NAMELIST/INCON3/CMN,CAB,CPV,                                       CON01750
     &CPY,CPX,CPZ,                                                       CON01760
     &CPW,CQR,CRS,CST,                                                   CON01770
     &CTU,CNF,G,GC                                                       CON01780
      NAMELIST/CONST1/KSJL,KSDF,KSGH,                                    CON01790
     &KSCD,KSDE,KSEF,                                                    CON01800
     &KSJK,KSKL,KZ,                                                      CON01810
     &KW,KRS,KST,                                                        CON01820
     &KON1,KON3,KON4,                                                    CON01830
     &KX,KHJ,KV,                                                         CON01840
     &KTU,KY                                                             CON01850
      NAMELIST/CONST2/AJL,CJL,LJL2,                                      CON01860
     &LJL1,DJF,LDF,                                                      CON01870
     &LCF1,ACF,LGH,                                                      CON01880
     &AGH,DGH,DCD,                                                       CON01890
     &LCD,LDEO,LJKO                                                      CON01900
      NAMELIST/CONST3/ACD,ZBEND1,ZBEND2,                                 CON01910
     &VOLJL,VOLDF,VOLDRM,                                                CON01920
     &VOLHJ,ZDF,ZJL,                                                     CON01930
     &LJL,DDF,DKL,                                                       CON01940
     &DEF,DJK,ZCD                                                        CON01950
      NAMELIST/CONST4/FCD,FGH,FDE,                                       CON01960
     &FEF,FJK,FKL,                                                       CON01970
     *ENTRGH,ENTRCD,BENDGH,                                              CON01980
     &BENDCD,EXITGH,EXITCD                                               CON01990
      NAMELIST/CONST5/FHV,XLLO,XFFO,                                     CON02000
     &TAMB,DROCFO,DROJLO,                                                CON02010
     &SIGMAA                                                             CON02020
      NAMELIST/OUTPUT/Q10,Q40,Q60,Q80,Q90,MFFO,MLLO,CCO,                 CON02030
     &XFFO,XLLO,RHCDFO,RHOJLO,RHOFFO,RHOLLO,                             CON02040
     &HSAT,HCDC,HAAO,HBBO,HJJO,HFG,RHCF,DMDVO,HXFFO,HXLLO                CON02050
C                                                                        CON02060
    ✓ READ(5,INCON0)                                                     CON02070
      READ(5,SCREEN)                                                     CON02080
      READ(5,SPHTR)                                                      CON02090
      READ(5,MNBANK)                                                     CON02100
```

```
      READ(5,ECON)
      READ(5,DESPH)
      READ(5,DRMDCR)
      READ(5,HDRDCR)
      READ(5,BOILER)
      READ(5,THERMO)
      READ(5,LOSSES)
C     CALCULATION OF PRELIMINARY CONSTANTS
C
      PI=3.1415927
      G=32.2
      PRAA=PRH2O
      VISCOA=VSCH2O
      THCONA=KH2O
      PRAN=PRSTM
      VISCON=VSCSTM
      THCONN=KSTM
      XASUME=0.05
      FCL=.015
      GC=32.2
      VALVEO=OPPNT
      KSCD=KSDHD
      KSDF=KSDSC
      KSDE=KSDF
      KSEF=KSDF
      CM=.11
      CPV=CM
      CPY=CM
      CPX=CM
      CPZ=CM
      CPW=CM
      KSGH=KSDCD
      KSJL=KSDMB
      KSJK=KSJL
      KSKL=KSJL
      ENTRCD=ENTHD
      ENTRGH=ENTDC
      BENDCD=BENDHD
      BENDGH=BENDMB
      EXITCD=1.0
      EXITGH=1.0
      PSAT=PDRUM+14.7
      HSAT=EXP(0.26452*ALOG(PSAT)+4.46703)
      HFG=922.15-0.40516*PSAT+1.717E-04*PSAT**2.0-4.219E-08*PSAT**3.0
      HV=HSAT+HFG
      HMMO=HV
      HF=HSAT
      TSAT=EXP(.22151*ALOG(PSAT)+4.77123)
      MFCOC=OILFLO/3600.0
      MACCO=AIRFLO/3600.0
      TRRO=TGASSC
      TVVO=TSCRN
      TWWO=TSPHTR
      TQRO=TRRO
      TSSO=TGASSH
      TMMO=TSAT
      TTTO=TGASMB
      TUUO=TGASEC
      TTLO=(TTTO+TUUO)/2.0
      TAMB=80.0
      MMMO=TOTSTM/3600.0
      MMME=MMMO*.0001
      MMMIII=SPHSTM/3600.0
      TNNO=SHOT
      TPPO=DSHOT
      PNNO=SHTP+14.7
      PMMO=PDRUM
      MMMII=DSHSTM/3600.0
      MNNO=MMMII
      TAAO=ECONIT
```

```
      TBBO=ECONOT
      VBBO=.01600488-.0000020146*TBBO+.000000036511*TBBO**2.0
     &-8.142E-11*TBBO**3.0+1.4081E-13*TBBO**4.0-1.148E-16*
     &TBBO**5.0+8.034E-20*TBBO**6.0
      CTCTO=HRFVCL*1000.0/3600.0
      HNNO=HSHOUT
      CFURAB=FFAS*1000.0/3600.0
      ARAC=RHASSC
      HPPC=HDSOUT
      LDF1=LAVSC
      LDF2=LDF1*NTUBSC
      CDF=DTUBSC*NTUBSC/12.0
      CDE=CDF
      DEF=DDE
      ADF=PI*DTUBSC**2.0*NTUBSC/(4.0*144.0)
      VOLDF=ADF*LDF1
      MASSV=MASSSC
      MASSW=MASSSH
      LJL1=LAVMB
      LJL2=NTUBMB*LJL1
      DJL=DTUBMB*NTUBMB/12.0
      DJK=DJL
      DKL=DJK
      AJL=PI*DTUBMB**2.0*NTUBMB/(4.0*144.0)
      VOLJL=AJL*LJL1
      MASSY=MASSMB
      MASSX=MASSEC
      MASSZ=MASSDS
      ZBENC1=HIDRM-HHDR
      LDF=ZBENC1
      ZDF=ZBENC1
      ZBENC2=HNCRM-HWTROM
      LJL=ZBENC2
      ZJL=ZBENC2
      ZCD=ZCF
      ZGH=ZJL
      DRODFO=0.0
      DRCJLO=0.0
      LAB=LTUBEC
      DAB=DTUBEC/12.0
      AREAEC=NTUBEC*LAB*PI*DAB*NPASSE
      DNP=DTUBDS/12.0
      LCD=LAVHD*NTUBHD
      LGH=LAVDD*NTUBDD
      DCD=DTUBHD*NTUBHD/12.0
      DGH=DTUBDD*NTUBDD/12.0
      ACD=NTUBHD*(PI*(DTUBHD/24.0)**2.0)
      AGH=NTUBDD*(PI*(DTUBDD/24.0)**2.0)
      VOLDFM=(PI*DSTMDM**2.0/(4.0*144.0))*LSTMDM
      VOLHJ=(PI*DWTRDM**2.0/(4.0*144))*LWTRDM
      HAAO=HECIN
      HBBO=HECOUT
      RHOF=63.8-0.01781*TSAT+1.132E-05*TSAT**2.0-6.786E-08*TSAT**3.0
      VF=1.0/RHOF
      VFG=524.0/PSAT-0.1
      VV=VF+VFG
      RHOV=1.0/VV
      RHOFG=RHOF-RHOV
      RHOMMO=RHOV
      RHONNO=RSHOUT
      RHOPPO=RDSOUT
      MAAO=MNNO
      MBBO=MAAO
C
C          CALCULATE THE TOTAL MASS OF FLUE GAS IN THE FURNACE
C
      MASSGR=RFLUE*FURVOL
C
C          CALCULATE THE TOTAL ENERGY ENTERING BOILER
C
```

```
      QQO=QTOTO*FURVOL
C
C          CALCULATE "LUMPED" LOWER HEATING VALUE OF FUEL/AIR MIX
C
      FHV=QQO/MFQQO
C
C          CALCULATE ENERGY ABSORBED BY RADIATION IN FURNACE-C
C
      Q10=QFURAB*ARAD
C
      Q20=Q10
C
C          CALCULATE THE STEFAN-BOLTZMAN CONSTANT MULTIPLIED BY THE
C          SCREEN AREA
C
      SIGMAA=Q10/((TQRO+460.0)**4.0-(TVVO+460.0)**4.0)
C
C          CALCULATE THE TOTAL FLUE GAS MASS FLOW RATE INTO BOILER
C
      MQQO=MFQQO+MAQQO
      MRRO=MQQO
      MSSO=MRRO
      MTTO=MSSO
      MUUO=MTTO
C
C          COMPUTE THE ENERGY TRANSFERRED TO THE WATER (LOWER) DRUM
C          BY THE DESUPERHEATER
C
      Q90=MNNO*(HNNO-HPPO)
      Q990=Q90
C
C          CALCULATE THE ENERGY TRANSFERRED TO THE MAIN BANK RISERS
C
      Q60=MMMO*(HMMO-HEEO)-Q20-Q990
      Q50=Q60
C
C          COMPUTE THE MAIN BANK HEAT TRANSFER COEFFICIENT-TUBE METAL
C          TO STEAM SIDES
C
      KY=AREAMB/1.782E06
C
C          COMPUTE THE MAIN BANK TUBE METAL TEMPERATURE
C
      TYYO=(Q60/(KY*PSAT**(4.0/3.0)))**(1.0/3.0)+TSAT
C
C          COMPUTE THE MAIN BANK HEAT TRANSFER COEFFICIENT-FLUE GAS
C          TO TUBE METAL
C
       TSTO=(TSSO+TTTO)/2.0
       KST=Q50/(MSSO**0.6*(TSTO-TYYO))
C
C          COMPUTE THE SCREEN BANK HEAT TRANSFER COEFFICIENT-TUBE
C          METAL TO STEAM SIDES
C
      KV=Q10/(PSAT**(4.0/3.0)*(TVVO-TSAT)**3.0)
C
C          COMPUTE THE HEAT TRANSFER TO THE SUPERHEATER
C
      Q40=MMMO*(HNNO-HMMO)
      Q30=Q40
C
C          COMPUTE THE SPECIFIC HEAT OF THE STEAM
C          IN THE SUPERHEATER
C
      CMN=Q40/(MMMO*(TNNO-TMMO))
C
C          COMPUTE THE SUPERHEATER HEAT TRANSFER COEFFICIENT-FLUE
C          GAS TO TUBE METAL-C
C
      TRSO=(TRRO+TSSO)/2.0
```

```
      KRS=Q30/(MRR0**0.6*(TRS0-TWW0))
C
C          COMPUTE THE HEAT TRANSFER TO THE ECONOMIZER
C
      Q80=MAA0*(HBB0-HAA0)
      Q70=Q80
C
C          COMPUTE THE SPECIFIC HEAT OF THE FEEDWATER
C           IN THE ECONOMIZER
C
      CAB=Q80/(MAA0*(TBB0-TAA0))
C
C          COMPUTE THE SPECIFIC HEAT OF FLUE GAS IN THE FURNACE
C
      CQR=(Q00-Q10)/(MRR0*(TQR0-TAMB))
C
C          COMPUTE THE SPECIFIC HEAT OF FLUE GAS IN THE SUPERHEATER
C
      CRS=Q30/(MRR0*(TRR0-TSS0))
C
C          COMPUTE THE SPECIFIC HEAT OF FLUE GAS IN THE MAIN BANK
C
      CST=Q50/(MSS0*(TSS0-TTT0))
C
C          COMPUTE THE SPECIFIC HEAT OF FLUE GAS IN THE ECONOMIZER
C
      CTU=Q70/(MTT0*(TTT0-TUU0))
C
C          COMPUTE THE ECONOMIZER HEAT TRANSFER COEFFICIENT-TUBE
C          METAL TO LIQUID
C
      KX=((.023*THCONA)/DAB)*(4.0/(PI*DAB*VISCOA*NTUBEC))**0.8
     &*PRAA**0.4*AREAEC
C
C          COMPUTE THE LMTD FOR THE ECONOMIZER
C
      LMTDAB=Q80/(KX*MAA0**0.8)
C
C          COMPUTE THE ECONOMIZER TUBE METAL TEMPERATURE
C
      EXPOEC=EXP((TBB0-TAA0)/LMTDAB)
      TXX0=(TAA0-TBB0*EXPOEC)/(1.0-EXPOEC)
C
C          COMPUTE THE ECONOMIZER HEAT TRANSFER COEFFICIENT-FLUE
C           GAS TO TUBE METAL
C
      KTU=Q70/(MTT0*(TTU0-TXX0))
C
C          COMPUTE THE DESUPERHEATER HEAT TRANSFER COEFFICIENT-TUBE
C          METAL TO STEAM
C
      KZ=((.023*THCONN)/DNP)*(4.0/(PI*DNP*VISCON*NTUBDS))
     &**0.8*PRAN**0.3*AREADS
C
C          COMPUTE THE DESUPERHEATER LMTD
C
      LMTDNP=Q90/(KZ*MNN0**0.8)
C
C          COMPUTE THE SPECIFIC HEAT OF STEAM IN THE DESUPERHEATER
C
      CNP=Q90/(MNN0*(TNN0-TPP0))
C
C          COMPUTE DESUPERHEATER TUBE METAL TEMPERATURE
C
      EXPODS=EXP((TNN0-TPP0)/LMTDNP)
      TZZ0=(TNN0-EXPODS*TPP0)/(1.0-EXPODS)
C
C          COMPUTE THE DESUPERHEATER HEAT TRANSFER COEFFICIENT-
C          WATER DRUM LIQUID TO TUBE METAL
C
```

```
      KHJ=Q99O/(TZZO-TSAT)
C
C          COMPUTE THE SUPERHEATER LMTD
C
      LMTDMN=(TNNO-TMMO)/(ALOG((TWWO-TMMO)/(TWWO-TNNO)))
C
C          CALCULATE THE SUPERHEATER HEAT TRANSFER COEFFICIENT-TUBE
C          METAL TO STEAM
C
      KW=Q40/(MMMO**0.8*LMTDMN)
C
C          CALCULATE THE THROTTLE VALVE FLOW COEFFICIENT
C
      KON4=MMMIII/(VALVE)*PNNO)
C
C          CALCULATE THE SUPERHEATER OUTLET DENSITY
C
      KON3=(PMMO+PNNO)/(RHOMMO+RHONNO)
      RHOMNO=(RHOMMO+RHONNO)/2.0
      KON1=((PMMO-PNNO)*RHOMNO)/MMMO**2.0
C
C          COMPUTE THE FRICTION FACTORS FOR THE DOWNCOMERS
C          AND THE RISERS
C
      FCD=1.0/(1.74-2.0*ALOG10(KSCD))
      FGH=1.0/(1.74-2.0*ALOG10(KSGH))
      FDE=1.0/(1.74-2.0*ALOG10(KSDE))
      FEF=1.0/(1.74-2.0*ALOG10(KSEF))
      FJK=1.0/(1.74-2.0*ALOG10(KSJK))
      FKL=1.0/(1.74-2.0*ALOG10(KSKL))
C-----------------------------------------------------------------------
C
C          START ITERATION TO BALANCE CIRCULATION LOOPS
C
C-----------------------------------------------------------------------
C
C          COMPUTE INITIAL VALUE OF RISER OUTLET MASS FLOW RATE
C
      MFFO=Q10/(XASUME*HFG)
      MLLO=Q50/(XASUME*HFG)
C
C          CALCULATE THE INITIAL DOWNCOMER ENTHALPY
C
   71 HCDO=((MFFO+MLLO-MBBO)*HF+MBBO*HBBO+0.0*(MFFO+MLLO)
     &*HV)/(MFFO+MLLO)
      HGHO=HCDO
C
C          COMPUTE THE INITIAL DRUM ENTHALPY
C
      HDRUMO=HCDO
C
C          COMPUTE MAIN BANK RISER INLET ENTHALPY
C
      MHHO=MLLO
      HJJO=HGHO+Q90/MHHO
C
C          CALCULATE THE RISER INLET DENSITY
C
      RHOCDO=RHOF
      RHOJJO=RHOF
C
C          COMPUTE THE DOWNCOMER DENSITY
C
      VCDO=((MFFO+MLLO-MBBO)*VF+MBBO*VBBO)
     &/(MFFO+MLLO)
      RHOCDO=1.0/VCDO
      RHOGHO=RHOCDO
C
C          CALCULATE THE RISER OUTLET QUALITY
C
```

```
      HDDO=HCDO
      XFFO=(Q1C+MFFO*(HF-HCDO))/(MFFO*HFG)
      XLLO=(Q5U+MLLO*(HF-HJJO))/(MLLO*HFG)
C
C          CALCULATE THE RISER OUTLET DENSITY
C
      RHOFFO=RHOF-XFFO*RHOFG
      RHOLLO=RHOF-XLLO*RHOFG
C
C          CALCULATE THE NONBOILING LENGTH OF THE RISERS
C
      ZBENC1=HNORM-HHCR
      LDF=ZBENC1
      LDEO=LDF*AMAX1((HF-HDDO),0.0)/((HDDO+XFFO*HFG)-HDDO)
      ZBENC2=HNORM-HWTRCM
      LJL=ZBENC2
      LJKO=LJL*AMAX1((HF-HJJO),0.0)/((HJJO+XLLO*HFG)-HJJO)
C
C          CALCULATE BOILING LENGTH OF RISERS
C
      LEFO=LDF-LDEO
      LKLO=LJL-LJKO
C
C          CALCULATE THE AVERAGE DENSITY IN THE SCREEN RISER
C
      RHODFO=(1.0/LDF)*(LEFO/((XFFO)*VFG)*ALOG(((XFFO
     &)/VF)*VFG+1.0)+RHODDO*LDEO)
C
C          CALCULATE THE AVERAGE DENSITY IN THE MAIN BANK RISER
C
      RHOJLO=(1.0/LJL)*(LKLO/((XLLO)*VFG)*ALOG((XLLO
     &*VFG)/VF+1.0)+RHOJJO*LJKO)
C
C          CALCULATE THE EFFECTIVE HEIGHT OF THE RISERS
C
      ZDEO=ZDF-LEFO
      ZJKO=ZJL-LKLO
      ZEFO=ZDF-ZDEO
      ZKLO=ZJL-ZJKO
C
C          COMPUTE THE TWO PHASE FLOW MULTIPLICATION FACTORS
C
      RGRAVE=24.794*XFFO**2.0-6.5066*XFFO+.9776
      RGRAVK=24.794*XLLO**2.0-6.5066*XLLO+.9776
      RACLE=15.4564*XFFO**2.0+18.4944*XFFO-.00007
      RACLJ=15.4564*XLLO**2.0+18.4944*XLLO-.00007
      RFRICE=-34.0822*XFFO**2.0+23.7164*XFFO+.8734
      RFRICK=-34.0822*XLLO**2.0+23.7164*XLLO+.8734
C
C          CALCULATE SECOND APPROXIMATION OF MASS FLOW RATE AT
C          EXIT OF SCREEN RISERSM
C
      RHOEEO=RHODDO
      MFFOO=((RHOCDO*G*ZCD-G*ZDEO*((RHODDO+RHOEEO)/2.0)
     &-G*ZEFO*RHOEEO*RGRAVE)/((FCD*LCD/DCD+ENTRCD
     &+BENDCD+EXITCD)/(2.0*ACD**2.0*RHOCDO)+((RHOEEO-RHODDO)
     &/(RHOEEO*RHODDO*ADF**2.0))+(4.0*FDE*LDEO*2.0
     &)/(2.0*DDF*(RHOEEO+RHODDO)*ADF**2.0)+RACLE/
     &(RHOEEO*ADF**2.0)+(4.0*FEF*LEFO*RFRICE)/
     &(2.0*DDF*RHOEEO*ADF**2.0)))**0.5
C
C          CALCULATE SECOND APPROXIMATION OF MASS FLOW RATE
C          AT EXIT OF MAIN BANK RISERS
C
      RHOKKO=RHOJJO
      MLLOO=((RHOGHO*G*ZGH-G*ZJKO*((RHOJJO+RHOKKO)/2.0)
     &-G*ZKLO*RHOKKO*RGRAVK)/((FGH*LGH/DGH+ENTRGH
     &+BENDGH+EXITGH)/(2.0*AGH**2.0*RHOGHO)+((RHOKKO-RHOJJO)
     &/(RHOKKO*RHOJJO*AJL**2.0))+(4.0*FJK*LJKO*2.0
     &)/(2.0*DJL*(RHOKKO+RHOJJO)*AJL**2.0)+RACLJ/
```

```
     &(RHOKKO*AJL**2.0)+(4.0*FKL*LKLO*RFRICK)/
     &(2.0*DJK*RHOKKO*AJL**2.0)))**0.5
C
C           COMPARE PREVIOUS APPROXIMATION FOR  RISER MASS
C           FLOW RATE TO CURRENT, IF WITHIN ERROR CRITERIA CONTINUE,
C           IF NOT, UPDATE AND THEN REITERATE-
C
      CHECK=0.0
      IF(ABS(MFFO-MFFOO).LT..01)GO TO 62
      MFFO=(MFFOO-MFFO)/2.0+MFFO
      CHECK=1.0
   62 IF(ABS(MLLO-MLLOO).LT..01)GO TO 64
      MLLO=(MLLOO-MLLO)/2.0+MLLO
      GO TO 71
   64 IF(CHECK.EQ.1.0)GO TO 71
C
C           COMPUTE INITIAL MASS OF LIQUID IN DRUM
C
      DMASLO=(VOLDRM*RHOCDO)/2.0
C
C           COMPUTE THE INITIAL DRUM "LIQUID" VOLUME
C
      DMDVO=VOLDRM/2.0
C
C           COMPUTE THE INITIAL ENERGY STORED IN DRUM LIQUID
C
      DMCHLO=DMASLO*HDRUMO
C
C           EQUATE INITIAL FLOW RATES
C
      MCDO=MFFO
      MGHO=MLLO
C
C           COMPUTE INITIAL MASS OF STEAM IN STEAM
C           DRUM
C
      DSTMO=VOLDRM*RHOV/2.0
C
C           COMPUTE HXFFO AND HXLLO
C
      HXFFO=HF+HFG*XFFO/2.0
      HXLLO=HF+HFG*XLLO/2.0
C
      WRITE(6,600)
  600 FORMAT(1H1)
      WRITE(6,INCON1)
      WRITE(6,601)
  601 FORMAT(1H0)
      WRITE(6,INCON2)
      WRITE(6,601)
      WRITE(6,INCON3)
      WRITE(6,601)
      WRITE(6,CONST1)
      WRITE(6,601)
      WRITE(6,CONST2)
      WRITE(6,601)
      WRITE(6,CONST3)
      WRITE(6,601)
      WRITE(6,CONST4)
      WRITE(6,601)
      WRITE(6,CONST5)
      WRITE(6,601)
      WRITE(6,600)
      WRITE(6,OUTPUT)
      WRITE(7,INCON1)
      WRITE(7,INCON2)
      WRITE(7,INCON3)
      WRITE(7,CONST1)
      WRITE(7,CONST2)
      WRITE(7,CONST3)
```

```
      WRITE(7,CONST4)                                                   CON07010
      WRITE(7,CONST5)                                                   CON07020
      WRITE(7,OUTPUT)                                                   CON07030
      STOP                                                              CON07040
      END                                                               CON07050
```

# APPENDIX B

```
 08/30/79  21.26.19

FILE: CSMP      FORTRAN  P1                       NAVAL POSTGRADUATE SCHOOL

//HOPEFULL JOB (2473,C567,NE31,,9),'WALKER SMC 1319',TIME=2             CSM00010
//   EXEC CSMPXV                                                        CSM00020
//X.SYSIN  DD  *                                                        CSM00030
********************************************************************    CSM00040
*                                                                       CSM00050
*                                                                       CSM00060
*                                                                       CSM00070
*********************************************************************   CSM00080
*                                                                       CSM00090
*          THIS D TYPE BOILER MODEL IS WRITTEN IN CSMP-III              CSM00100
*          COMPUTER LANGUAGE.  IT IS A NONLINEAR MODEL                  CSM00110
*          WHICH UTILIZES A SET OF INITIAL CONDITIONS AND               CSM00120
*          OTHER DATA PREPARED BY AN INITIAL CONDITION FORTRAN          CSM00130
*          MODEL WHICH PRECEDES THIS ONE.  THE MODEL IS GOOD            CSM00140
*          FOR SMALL TRANSIENTS AROUND THE OPERATING POINT              CSM00150
*          SPECIFIED BY THE INITIAL CONDITION PROGRAM.                  CSM00160
*                                                                       CSM00170
*********************************************************************   CSM00180
INITIAL                                                                 CSM00190
CONST DRA41=0.0,DRA42=0.0,DRA43=0.0,DRA44=0.0,DRA45=0.0,DRA46=0.0, ...  CSM00200
DRA47=0.0,DRA48=0.0,DRA31=0.0,DRA32=0.0,DRA33=0.0,DRA34=0.0,...         CSM00210
DRA35=0.0,DRA36=0.0,DRA37=0.0,DRA38=0.0                                 CSM00220
 CONST ONE=1.0, ...                                                     CSM00230
 TRRO=  2563.0000    ,TVVO=  600.00000    ,TWWO=  1033.0000    ,TYYO=...CSM00240
   515.42749    ,TZZO=  600.99976    ,TXXO=  360.36450                  CSM00250
 CONST TWO=2.0, ...                                                     CSM00260
 DMJHO=  2754667.0    ,DMASSO=  5415.8164    ,MAAO=  45.000000 ,TAAO=...CSM00270
   254.00000    ,MFOOO=  3.3074999    ,MAQQO=  55.898880    ,MNNO=...   CSM00280
   7.7500000    ,MMMO=  45.000000    ,VALVEO= 0.50999999    ,MQQO=...   CSM00290
   59.206375    ,CMN= 0.65523028    ,CAB=  1.0761900,CPV=0.10999995,... CSM00300
 CPY= 0.10999995    ,CPX= 0.10999995    ,CPZ= 0.10999995    ,CPW=    ...CSM00310
  0.10999995,DMJHLO=3961626.0,DMASLO=8002.2000,DMDVO=163.65698          CSM00320
 CONST THREE=3.0, ...                                                   CSM00330
 DRODFO= 0.0            ,DROJLO= 0.0            ,MMME= 0.44999979E-02,... CSM00340
                 MGHO=  662.70825    ;MBRO=  45.000000    ,LSTMDM=   ...  CSM00350
   16.666666    ,DSTMDM=  60.000000    ,MCDO=980.02734,CLCVO=163.66     CSM00360
 CONST FOUR=4.0, ...                                                    CSM00370
 KSJL= 0.59999991E-04,KSDF= 0.29999996E-04,KSGH= 0.49999999E-05,KSCD=...CSM00380
  0.49999999E-05,KSDE= 0.29999996E-04,KSEF= 0.29999996E-04,  ...        CSM00390
KSJK=0.59999991E-04, ...                                                CSM00400
 KSKL= 0.59999991E-04,AJL=  10.678426    ,DJL=  196.57166    ,LJL2=...  CSM00410
   28420.000    ,LJL1=  10.000000    ,DDF=  35.897476,LDF=15.750000,... CSM00420
 LDF1=  12.700000    ,ADF=  4.0646048    ,LGH=  25.000000    ,AGH=...   CSM00430
   1.4451332,SAMPL=250,RISTIM=10.0                                      CSM00440
 CONST FIVE=5.0, ...                                                    CSM00450
 DGH=  1.9183321    ,DCD=  4.6699991    ,LCD=  94.500000    ,LDEO=   ...CSM00460
   2.6166515    ,LJKO= 0.80500102    ,ACD=  2.8547773,MASSV=7951.3984...CSM00470
,MASSW=  10752.000    ,MASSY=  28192.000    ,MASSX=  24443.000,MASSZ=...CSM00480
   1617.0000    ,ZBENC1=  15.750000    ,FCD= 0.81023693E-01, ...        CSM00490
 FDE= 0.92714846E-01,FEF= 0.92714846E-01,FGH=0.81023693E-01             CSM00500
 CONST SIX=6.0, ...                                                     CSM00510
 ZBENC2=  12.410001    ,MASSDR= 71.395            ,VOLJL=  106.78426,VOLD...CSM00520
F= 51.620468    ,VOLDRM=  327.31396    ,VOLHJ=  98.174744               CSM00530
 CONST SEVEN=7.0, ...                                                   CSM00540
 COR= 0.31599814    ,CFS= 0.30453670    ,CST= 0.29042804    ,CTU=    ...CSM00550
  0.26026064    ,CNP= 0.58347189    ,KNP=  18.508820    ,KW=2.0997734,...CSM00560
 SIGMAA= 0.21132812E-09,KRS= 0.87189436    ,KST=  2.2037563             CSM00570
 CONST EIGHT=8.0, ...                                                   CSM00580
 KTU= 0.44126600    ,ENTRGH= 0.99999964E-01,ENTRCD= 0.99999964E-01,...  CSM00590
                 BENDCD= 0.99999964E-01,EXITGH=  1.0000000,EXITCD=...   CSM00600
  1.0000000    ,HAAO=  221.00000    ,KON1= 0.10645876E-01,...           CSM00610
 KON4= .10777515    ,FJK= 0.98196149E-01,FKL= 0.98196149E-01,...        CSM00620
 GC=  32.199997    ,TAMB=  80.000000    ,ZCD=  15.750000    ,ZDF=    ...CSM00630
   15.750000    ,ZJL=  12.410001    ,LJL=  12.410001    ,...            CSM00640
BENDGH=0.14999998,KON3=647.71460,G=32.199997,DSTMO=249.59802            CSM00650
 CONST NINE=9.0, ...                                                    CSM00660
 KX=  10.037373    ,KZ=  14.930669    ,KV= 0.32769613E-05,...           CSM00670
 FHV=  19300.496    ,DDE=  35.897476    ,DKL=  196.57166    ,DEF=...    CSM00680
   35.897476    ,DJK=  196.57166,KY=0.36683502E-02,...                  CSM00690
 DRA10=0.0,DRA20=0.0,XFFO=0.18950000E-01,...                            CSM00700
```

```
XLLO=0.40000000E-01,MFFO=980.02734,MLLO=662.70825                       CSM00710
CONST TEN=10.0,...                                                      CSM00720
DRA11=0.0,DRA12=0.0,DRA13=0.0,DRA14=0.0,DRA15=0.0,DRA16=0.0,...         CSM00730
DRA17=0.0          ,DRA21=0.0,DRA22=0.0,DRA23=0.0,DRA24=0.0,...         CSM00740
FCL=.015,CCO=63836.395,ZGF=12.410001                      ,...          CSM00750
DRA25=0.0,DRA26=0.0,DRA27=0.0,HXLLO=505.81 ,HXFFO=502.34                CSM00760
DYNAMIC                                                                 CSM00770
*                                                                       CSM00780
*          INPUT EQUATIONS                                              CSM00790
*                                                                       CSM00800
VALVE=.015*RAMP(10.0)-.015*RAMP(20.0)+.51                               CSM00810
MNN=MNNO                                                                CSM00820
MAA=MAAO                                                                CSM00830
TAA=TAAO                                                                CSM00840
*                                                                       CSM00850
*          COMPUTE THE TOTAL FLUE GAS FLOW RATE INTO BOILER             CSM00860
*                                                                       CSM00870
MCC=MCCO                                                                CSM00880
*                                                                       CSM00890
*          COMPUTE THE ENERGY ENTERING THE BOILER                       CSM00900
*                                                                       CSM00910
QQ=QQO                                                                  CSM00920
*                                                                       CSM00930
*          COMPUTE THE ENERGY TRANSFERRED TO THE SCREEN RISERS          CSM00940
*          VIA RADIATION                                                CSM00950
*                                                                       CSM00960
Q1=SIGMAA*((TRR+460.0)**4.0-(TVV+460.0)**4.0)                           CSM00970
*                                                                       CSM00980
*          COMPUTE THE RATE EQUATION FOR FURNACE FLUE GAS               CSM00990
*          TEMPERATURE                                                  CSM01000
*                                                                       CSM01010
DTRR=(QQ-Q1-MRR*CQR*(TRR-TAMB))/(MASSQR*CQR)                            CSM01020
*                                                                       CSM01030
*          COMPUTE THE FLUE GAS TEMPERATURE                             CSM01040
*                                                                       CSM01050
TRR=INTGRL(TRRO,DTRR)                                                   CSM01060
*                                                                       CSM01070
*          COMPUTE THE TEMPERATURE OF THE FLUE GAS                      CSM01080
*          LEAVING THE SUPERHEATER                                      CSM01090
*                                                                       CSM01100
PHI1=2.0*MRR**0.4*CRS/KRS                                               CSM01110
TSS=(TRR*(PHI1-1.0)+2.0*TWW)/(PHI1+1.0)                                 CSM01120
*                                                                       CSM01130
*          COMPUTE THE SUPERHEATER ENERGY TRANSFER                      CSM01140
*          FLUE GAS TO TUBE METAL                                       CSM01150
*                                                                       CSM01160
Q3=MRR*CRS*(TRR-TSS)                                                    CSM01170
*                                                                       CSM01180
*          COMPUTE THE MAIN BANK ENERGY TRANSFER                        CSM01190
*          FLUE GAS TO TUBE METAL                                       CSM01200
*                                                                       CSM01210
Q5=MSS*CST*(TSS-TTT)                                                    CSM01220
*                                                                       CSM01230
*          COMPUTE THE TEMPERATURE OF THE FLUE GAS                      CSM01240
*          LEAVING THE MAIN BANK                                        CSM01250
*                                                                       CSM01260
PHI2=2.0*MSS**0.4*CST/KST                                               CSM01270
TTT=(TSS*(PHI2-1.0)+2.0*TYY)/(PHI2+1.0)                                 CSM01280
*                                                                       CSM01290
*          COMPUTE THE TEMPERATURE OF THE FLUE GAS LEAVING-             CSM01300
*          THE ECONOMIZER                                               CSM01310
*                                                                       CSM01320
PHI3=2.0*CTU/KTU                                                        CSM01330
TUU=(TTT*(PHI3-1.0)+2.0*TXX)/(PHI3+1.0)                                 CSM01340
*                                                                       CSM01350
*          COMPUTE ECONOMIZER ENERGY TRANSFER                           CSM01360
*          FLUE GAS TO TUBE METAL                                       CSM01370
*                                                                       CSM01380
Q7=MTT*CTU*(TTT-TUU)                                                    CSM01390
*                                                                       CSM01400
```

```
*
*          USE CONTINUITY RELATIONSHIP TO COMPUTE THE MASS
*          FLOW RATE UP THE RISERS
*
MLL=MJJ-DRHOJL*VOLJL
MFF=MDD-DRHODF*VOLDF
DRA18=DERIV(DRA10,RHOJL)
DRA28=DERIV(DRA20,RHODF)
PROCEDURE DRHOJL=FILTR1(DRA14)
IF(KEEP.NE.1)GO TO 1
DRHOJL=(DRA18+DRA17+DRA16+DRA15+DRA14+DRA13+DRA12+DRA11+...
     DRA31+DRA32+DRA33+DRA34+DRA35+DRA36+DRA37+DRA38)/16.0
DRA53=DRA52
DRA52=DRA51
DRA51=DRA31
DRA31=DRA32
DRA32=DRA33
DRA33=DRA34
DRA34=DRA35
DRA35=DRA36
DRA36=DRA37
DRA37=DRA38
DRA38=DRA11
DRA11=DRA12
DRA12=DRA13
DRA13=DRA14
DRA14=DRA15
DRA15=DRA16
DRA16=DRA17
DRA17=DRA18
1   CONTINUE
ENDPROCEDURE
PROCEDURE DRHODF=FILTR2(DRA24)
IF(KEEP.NE.1)GO TO 2
DRHODF=(DRA28+DRA27+DRA26+DRA25+DRA24+DRA23+DRA22+DRA21+...
     DRA41+DRA42+DRA43+DRA44+DRA45+DRA46+DRA47+DRA48)/16.0
DRA63=DRA62
DRA62=DRA61
DRA61=DRA41
DRA41=DRA42
DRA42=DRA43
DRA43=DRA44
DRA44=DRA45
DRA45=DRA46
DRA46=DRA47
DRA47=DRA48
DRA48=DRA21
DRA21=DRA22
DRA22=DRA23
DRA23=DRA24
DRA24=DRA25
DRA25=DRA26
DRA26=DRA27
DRA27=DRA28
2    CONTINUE
ENDPROCEDURE
*
*          COMPUTE THE AVERAGE DENSITY IN THE RISERS
*
*
RHOJL=(1.0/LJL)*((LKL/(XLL*VFG))*ALOG((XLL/VF)*VFG+1.0)...
     +RHOJJ*LJK)
RHODF=(1.0/LDF)*((LEF/(XFF*VFG))*ALOG((XFF/VF)*VFG+1.0)...
     +RHODD*LDE)
RHOFF=RHOF-XFF*RHOFG
RHOLL=RHOF-XLL*RHOFG
*          COMPUTE THE MAIN BANK ENERGY TRANSFER -
*          TUBE METAL TO MAIN BANK MIXTURE
*
C6=KY*PSAT**(4.0/3.0)*(TYY-TSAT)**3.0
```

```
*
*           COMPUTE THE SCREEN RISER ENERGY TRANSFER -
*           TUBE METAL TO SCREEN RISER MIXTURE
*
Q2=KV*PSAT**(4.0/3.0)*(TVV-TSAT)**3.0
*
*           COMPLTE THE RISER AVERAGE ENTHALPYS
*
HDF=HDD+XFF*HFG/2.0
HJL=HJJ+XLL*HFG/2.0
*
*           COMPLTE THE RISER OUTLET ENTHALPYS
*
HFF=HF+XFF*HFG
HLL=HF+XLL*HFG
*
*           COMPUTE THE RISER EFFECTIVE HEIGHTS
*
ZDE=ZDF-LEF
ZJK=ZJL-LKL
ZKL=ZJL-ZJK
ZEF=ZDF-ZDE
*
*           COMPUTE THE SPECIFIC VOLUME OF THE ECONOMIZER
*           OUTLET LIQUID
*
VBB=.01600486-.0000020146*TBB+.00000036511*TBB**2.0...
-8.142E-11*TBB**3.0+2.403E-13*TBB**4.0-1.148E-16*TBB**5.0...
+6.034E-20*TBB**6.0
*
*           COMPLTE THE RATE EQUATION FOR RISER OUTLET QUALITY
*
DHXLL=(MGG*(HJJ-HF-XLL*HFG/2.0)+Q6-MLL*XLL*HFG/2.0)/(RHOJL*VOLKL)
HXLL=INTGRL(HXLLO,DHXLL)
XLL=(HXLL-HF)*2.0/HFG
DHXFF=(MDD*(HDD-HF-XFF*HFG/2.0)+Q2-MFF*XFF*HFG/2.0)/(RHODF*VOLEF)
HXFF=INTGRL(HXFFO,DHXFF)
XFF=(HXFF-HF)*2.0/HFG
*
*
*
*           COMPLTE THE RISER BOILING VOLUME
*
VOLEF=VOLDF*LEF/LDF
VOLKL=VOLJL*LKL/LJL
*
*           COMPUTE THE NONBOILING LENGTH OF THE RISERS
*
LDE=LDF*(HF-HDD)/((HF+XFF*HFG)-HDD)
LJK=LJL*(HF-HJJ)/((HF+XLL*HFG)-HJJ)
*
*           COMPUTE THE BOILING LENGTH OF THE RISERS
*
LKL=LJL-LJK
LEF=LDF-LDE
*
*
*
*
*           COMPUTE THE MASS RATE EQUATION FOR STEAM CONDENSING IN
*           THE DRUM
*
MCOND=560.93*(PMM/(TMM+460.0)**0.5-PSAT/(TSAT+460.0)**0.5)...
     +.02568
*
*           COMPUTE THE RATE EQUATION FOR DRUM LIQUID MASS
*
DOMASL=MLL*(1.0-XLL)+MFF*(1.0-XFF)+MCOND+MBBO-MCC-MGG
*
*           COMPUTE THE DRUM LIQUID MASS
```

```
*                                                                        CSM02810
DMASL=INTGRL(DMASLO,DDMASL)                                              CSM02820
*                                                                        CSM02830
*           COMPUTE THE RATE EQUATION FOR ENERGY IN THE DRUM LIQUID      CSM02840
*                                                                        CSM02850
DDMDHL=MLL*(1.0-XLL)*HF+MFF*(1.0-XFF)*HF+MCOND*HFG+MBB*HBB...            CSM02860
      -MCC*HCC-MGG*HGG                                                   CSM02870
*                                                                        CSM02880
*           COMPUTE THE ENERGY IN THE DRUM LIQUID                        CSM02890
*                                                                        CSM02900
DMDHL=INTGRL(DMDHLO,DDMDHL)                                              CSM02910
*                                                                        CSM02920
*           COMPUTE THE ENTHALPY OF THE DRUM LIQUID                      CSM02930
*                                                                        CSM02940
DH=DMDHL/DMASL                                                           CSM02950
*                                                                        CSM02960
*                                                                        CSM02970
*           COMPUTE THE DRUM SPECIFIC VOLUME                             CSM02980
*                                                                        CSM02990
CRYUND=PCU*(MLL+MFF)                                                     CSM03000
PROCEDURE RISE2=FILTR4(CRYUND)                                           CSM03010
RISE1=DELAY(250,RISTIM,CRYUND)                                           CSM03020
RISE2=CRYUND                                                             CSM03030
IF(VALVE.GT..51)GO TO 55                                                 CSM03040
RISE=RISE2                                                               CSM03050
GO TO 57                                                                 CSM03060
55      RISE=RISE1                                                       CSM03070
57      CONTINUE                                                         CSM03080
ENDPROCEDURE                                                             CSM03090
DDMDV=((MFF+MLL-MBB)*VF+PCU*(MFF+MLL)*VV+MBBO*VBB-(MCC+MGG)*VF+MCOND...  CSM03100
      *VFG-RISE*VV)                                                      CSM03110
DMDV=INTGRL(DMDVO,DDMDV)                                                 CSM03120
*                                                                        CSM03130
*           COMPUTE THE DRUM LEVEL                                       CSM03140
*                                                                        CSM03150
LEVEL=(DMDV-VOLDRM/2.0)/(LSTMDM*CSTMDM)                                  CSM03160
*           COMPUTE THE DOWNCOMER ENTHALPY                               CSM03170
*                                                                        CSM03180
HCD=((MFF+MLL-MBB)*HF+MBB*HBB)/(MFF+MLL)                                 CSM03190
HGH=HCD                                                                  CSM03200
HDD=HCD                                                                  CSM03210
HCC=HCD                                                                  CSM03220
HGG=HGH                                                                  CSM03230
*                                                                        CSM03240
*           COMPUTE THE DOWNCOMER SPECIFIC VOLUME AND DENSITY            CSM03250
*                                                                        CSM03260
VCD=((MFF+MLL-MBB)*VF+MBB*VBB)/(MFF+MLL)                                 CSM03270
RHOCD=1.0/VCD                                                            CSM03280
RHOGH=RHOCD                                                              CSM03290
*                                                                        CSM03300
*           COMPUTE THE SATURATION PRESSURE AND TEMPERATURE              CSM03310
*           CORRESPONDING TO THE DOWNCOMER ENTHALPY                      CSM03320
*                                                                        CSM03330
PSAT=EXP((ALOG(HSAT)-4.45708)/.26452)                                    CSM03340
TSAT=EXP((.22151*ALOG(PSAT)+4.77123))                                    CSM03350
*                                                                        CSM03360
*           COMPUTE THE ENTHALPY OF THE LIQUID ENTERING THE              CSM03370
*           MAIN BANK RISER                                              CSM03380
*                                                                        CSM03390
HJJ=HGH+Q9/MHH                                                           CSM03400
*                                                                        CSM03410
*           COMPUTE THE RATE EQUATION FOR THE MAIN BANK AND              CSM03420
*           SCREEN RISER TUBE METAL TEMPERATURES                         CSM03430
*                                                                        CSM03440
DTVV=(Q1-Q2)/(MASSV*CPV)                                                 CSM03450
DTYY=(Q5-Q6)/(MASSY*CPY)                                                 CSM03460
*                                                                        CSM03470
*           COMPUTE THE SCREEN AND MAIN BANK RISER TUBE                  CSM03480
*           METAL TEMPERATURES                                           CSM03490
*                                                                        CSM03500
```

```
TVV=INTGRL(TVVC,DTVV)
TYY=INTGRL(TYY0,DTYY)
*
*          COMPUTE THE HEAT TRANSFER FOR THE DESUPERHEATER
*          -STEAM TO TUBE METAL
*
Q9=CNP*MNN*(TNN-TPP)
*
*          COMPUTE THE TEMPERATURE OF THE STEAM LEAVING THE
*          DESUPERHEATER
*
TPP=(TNN-TZZ)/(EXP(KNP/(CNP*MNN**0.2)))+TZZ
*
*          SET THE DOWNCOMER ENTRANCE AND EXIT TEMPERATURES
*          EQUAL TO THE SATURATION TEMPERATURE CORRESPONDING
*          TO DRUM ENTHALPY
*
TGG=TSAT
THH=TSAT
TCC=TSAT
TDD=TSAT
*
*          COMPUTE THE ENERGY TRANSFER FOR THE DESUPERHEATER
*          TUBE METAL TO DRUM LIQUID
*
Q99=KZ*(TZZ-THH)
*
*          COMPUTE THE RATE EQUATION FOR DESUPERHEATER TUBE METAL
*          TEMPERATURE
*
DTZZ=(Q9-Q99)/(MASSZ*CPZ)
*
*          COMPUTE THE DESUPERHEATER TUBE METAL TEMPERATURE
*
TZZ=INTGRL(TZZ0,DTZZ)
*
*          COMPUTE THE ECONOMIZER ENERGY TRANSFER-TUBE METAL
*          TO FEED WATER
*
Q8=MAA*CAB*(TBB-TAA)
*
*          COMPUTE THE FEED TEMPERATURE AT OUTLET
*          OF ECONOMIZER
*
TBB=(TAA-TXX)/(EXP(KX/(CAB*MAA**0.2)))+TXX
*
*          COMPUTE THE RATE EQUATION FOR THE ECONOMIZER TUBE
*          METAL TEMPERATURE
*
DTXX=(Q8-Q7)/(MASSX*CPX)
*
*          COMPUTE THE ECONOMIZER TUBE METAL TEMPERATURE
*
TXX=INTGRL(TXX0,DTXX)
*
*          COMPUTE THE SUPERHEATED STEAM OUTLET TEMPERATURE
*
TNN=(TMM-TWW)/(EXP(KW/(CMN*MNN**0.2)))+TWW
*
*          COMPUTE THE SUPERHEATER ENERGY TRANSFER-TUBE METAL
*          TO STEAM
Q4=CMN*MNN*(TNN-TMM)
*
*          COMPUTE THE RATE EQUATION FOR SUPERHEATER TUBE METAL
*          TEMPERATURE
*
DTWW=(Q3-Q4)/(MASSW*CPW)
*
*          COMPUTE THE SUPERHEATER TUBE METAL TEMPERATURE
*
```

```
TWW=INTGRL(TWWO,DTWW)
*
*             COMPUTE THE IMPLICIT EQUATION FOR TOTAL STEAM
*             FLOW RATE FROM BOILER
*
MMM=IMPL(MMMO,MMME,MMMIMP)
*
*             COMPUTE THE SUPERHEATER OUTLET PRESSURE
*
PMM=SQRT(PSAT**2.0-2.0*KON3*KON1*MMM**2.0)
MMMIII=PMM*KON4*VALVE
MMMII=MNNO
MMMIMP=MMMII+MMMIII
*
*             EQUATE THE FLUE GAS MASS FLOW RATES
*
MRR=MQQ
MSS=MRR
MTT=MSS
MLL=MTT
*
*             SET RISER INLET DENSITY EQUAL TO
*             SATURATED LIQUID DENSITY
*
RHOEE=RHOF
RHOJJ=RHOF
RHODD=RHOEE
RHOKK=RHOJJ
*
*             EQUATE DOWNCOMER FLOW RATES TO RISER ENTRANCE FLOW
*             RATES AND SET RISER ENTRANCE FLOW RATES TO THE
*             FLOW RATES AT THE INITIAL TIME
*
MHH=MGG
MCC=MDD
MGG=MJJ
MDD=MFFO
MJJ=MLLO
*
*             COMPUTE THE DERIVATIVE OF AVERAGE RISER DENSITY
*
*
*             COMPUTE THE STEAM MASS RATE EQUATION FOR THE STEAM
*             DRUM
DDSTM=XFF*MFF+XLL*MLL-MCOND-MMM
*
*             COMPUTE THE DRUM STEAM MASS
*
DSTM=INTGRL(DSTMO,DDSTM)
*
*             COMPUTE THE VOLUME OF STEAM IN THE STEAM DRUM
*
VOLSTM=VOLDRM-DMASL/RHOF
*
*             COMPUTE THE DENSITY OF STEAM IN THE STEAM DRUM
*
RHOSTM=DSTM/VOLSTM
RHOMM=RHOSTM
VVMM=1.0/RHOMM
VFGMM=VVMM-VF
*
*             COMPUTE THE STEAM DRUM STEAM OUTLET PRESSURE
*
PRESSM=524.0/(VFGMM+.1)
PROCEDURE PMM=FILTR6(PRESSM)
IF(PRESSM.LT.0.0)CALL DEBUG (3,0.0)
PMM=PRESSM
ENDPROCEDURE
*
*             COMPUTE THE STEAM DRUM STEAM OUTLET TEMPERATURE
```

```
*                                                                       CSM04910
TMM=EXP(.22151*ALOG(PMM)+4.77123)                                       CSM04920
*                                                                       CSM04930
*          SOLVE FOR THE ECONOMIZER FEED OUTLET ENTHALPY                CSM04940
*                                                                       CSM04950
HBB=(MBB*HAA0+C8)/MBB                                                   CSM04960
*                                                                       CSM04970
*          FEEDRATE EQUATION                                            CSM04980
*                                                                       CSM04990
MBB=MBB0                                                                CSM05000
*                                                                       CSM05010
*          TWO PHASE FLOW MULTIPLIER EQUATIONS                          CSM05020
*                                                                       CSM05030
RGRAVE=24.794*XFF**2.0-6.5066*XFF+.9776                                 CSM05040
RGRAVK=24.794*XLL**2.0-6.5066*XLL+.9776                                 CSM05050
RACLE=15.4564*XFF**2.0+18.4944*XFF-.00007                               CSM05060
RACLJ=15.4564*XLL**2.0+18.4944*XLL-.00007                               CSM05070
RFRICE=-34.0822*XFF**2.0+23.7164*XFF+.8734                              CSM05080
RFRICK=-34.0822*XLL**2.0+23.7164*XLL+.8734                              CSM05090
*                                                                       CSM05100
*          STATE POINT EQUATIONS                                        CSM05110
*                                                                       CSM05120
HSAT=DH                                                                 CSM05130
HF=HSAT                                                                 CSM05140
HFG=922.15-0.40516*PSAT+1.717E-04*PSAT**2.0-4.219E-08...                CSM05150
     *PSAT**3.0                                                         CSM05160
HV=HSAT+HFG                                                             CSM05170
KHCF=63.8-0.01781*TSAT+1.132E-05*TSAT**2.0-6.786E-08...                 CSM05180
```

# APPENDIX C

G Anticipated Performance

| | Endurance 2 Boilers | Design Rated Full Power | Maximum Intermittent Power | Endurance 1 Boiler | Boiler Overload | |
|---|---|---|---|---|---|---|
| Ra of Operation - Per Cent | 56 | 83 | 97 | 114 | 120 | |
| To l Steam Generated lb/hr | 195,000 | 290,000 | 340,000 | 400,000 | 420,000 | |
| Su rheated Steam lbs/hr. | 155,000 | 235,000 | 265,000 | 300,000 | 320.000 | |
| De perheated Steam lbs/hr. | 40,000 | 55,000 | 75,000 | 100,000 | 100.000 | |
| Bo r Drum Pressure psig | 690 | 690 | 690 | 690 | 690 | |
| Su rheater Outlet Pressure psig | 665 | 630 | 610 | 580 | 570 | |
| Su rheater Outlet Temperature °F | 912 | 914 | 980 | 898 | 895 | |
| De perheated Steam Outlet Pressure psig | 651 | 606 | 558 | 480 | 470 | |
| De perheated Steam Outlet Temperature °F | 635 | 659 | 680 | 690 | 690 | |
| Ec omizer Inlet Pressure psig | 715 | 726 | 733 | 749 | 754 | |
| Ec omizer Inlet Temperature °F | 250 | 250 | 250 | 250 | 250 | |
| Ec omizer Outlet Pressure psig | 703 | 705 | 703 | 708 | 710 | |
| Ec omizer Outlet Temperature °F | 355 | 372 | 372 | 377 | 380 | |
| Ca ig Air Inlet Temperature °F | 100 | 100 | 100 | 100 | 100 | |
| To l Air Flow lb/hr | 242,229 | 368,092 | 433,589 | 513,154 | 540,952 | |
| To l Oil Flow lb/hr | 14,333 | 21,781 | 25,656 | 30,364 | 32,009 | |
| An cipated Efficiency % | 85.7 | 84.4 | 83.8 | 83.0 | 82.7 | |
| Gu anteed Efficiency % | 85.7 | 84.4 | 83.8 | 83.0 | 82.7 | |
| Ra tion and Unaccounted for Losses % | .99 | .99 | .95 | 1.01 | .98 | |
| Ex ss Air % | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | |
| Ca on Dioxide % | 13.0 | 13.0 | 13.0 | 13.0 | 13.0 | |
| Nu ber of Burners in Operation | 6 | 6 | 6 | 6 | 6 | |
| Th ttle or Non-Throttle of Air Doors | N.T. | N.T. | N.T. | N.T. | N.T. | |
| Dra Loss - Total Inches Water | 13.74 | 33.98* | 47.96 | 69.51 | 76.22** | 93.48*** |
| Thr gh Double Casing | 1.33 | 3.09 | 4.28 | 6.00 | 6.67 | 10.22 |
| Thr gh Burner Register | 2.60 | 6.00 | 8.50 | 11.50 | 13.00 | 15.88 |
| Thr gh Boiler & Superheater | 4.83 | 12.29 | 18.14 | 25.61 | 28.15 | 38.32 |
| Thr gh Economizer | 4.98 | 12.60 | 17.04 | 26.40 | 28.40 | 29.06 |
| Gas emperature Leaving Superheater Screen °F | 2471 | 2594 | 2642 | 2686 | 2699 | |
| Gas emperature Leaving Superheater °F | 1826 | 1961 | 2021 | 2085 | 2103 | |
| Gas emperature Leaving Main Bank °F | 694 | 774 | 812 | 856 | 872 | |
| Gas emperature Leaving Economizer °F | 373 | 427 | 453 | 484 | 498 | |
| Hea Release KB/Hr/Sq. Ft. Radiant Heat Absorbing Sur ce | 447 | 680 | 800.6 | 948 | 999 | |
| Hea Release KB/Hr/Sq. Ft. Total Heating Surface | 15.5 | 23.6 | 28.0 | 32.9 | 34.7 | |
| Hea Release KB/Hr/Cu. Ft. Furnace Volume | 183.9 | 279.5 | 329.2 | 389.6 | 410.8 | |
| Fur ce Heat Absorption KB/Hr./Sq. Ft | 128.4 | 171.0 | 191.1 | 213.19 | 221.5 | |
| Hea Absorption First Water Screen Row KB/Hr/Sq. Ft. (Max.) | 210 | 231 | 255.3 | 288 | 256 | |
| Hea Absorption Maximum KB/Hr./Sq. Ft (Furnace Screen) | 210 | 231 | 255.3 | 288 | 256 | |

Dr Losses (Full Power) Based On 241 Cu. Ft. of 100°F Air/Lb. of Fuel Oil

*D ft Losses (Overload) Based On 241 Cu. Ft. of 100°F Air/Lb. of Fuel Oil

** aft Losses (Overload) Based on 260 Cu. Ft. of 68°F Air/Lb. of Fuel Oil

II. Anticipated Metal Temperature Degree F.

| | Endurance 2 Boilers | Design Rated Full Power | Maximum Intermittent Power | Endurance 1 Boiler | Boiler Overload |
|---|---|---|---|---|---|
| Water Screen Tubes Outside | 644 | 656 | 661 | 667 | 680 |
| Water Screen Tubes Inside | 554 | 554 | 554 | 554 | 555 |
| Superheater Tubes Outside - Maximum | 1022 | 1046 | 1049 | 1048 | 1048 |
| Superheater Tubes Inside - Maximum | 1044 | 1020 | 1019 | 1014 | 1012 |
| Maximum Inner Casing Temperature | 800 | 825 | 835 | 850 | 870 |
| Maximum Outer Casing Temperature at way of Structural ties | 350 | 350 | 350 | 350 | 350 |
| Maximum Outer Casing Temperature | 145 | 145 | 145 | 145 | 145 |

Tube Data

| | O.D. | M.W.T. | No. | Material |
|---|---|---|---|---|
| Side Wall and Roof | 2" | .134" | 71 | MIL-T-16286 CL. A* |
| Rear Wall | 2" | .134" | 54 | MIL-T-16286 CL. A* |
| Front Wall | 2" | .134" | 22 | MIL-T-16286 CL. A* |
| Screen Bank | 2" | .134" | 102 | MIL-T-16286 CL. A* |
| Superheater | 1.5" | .120 | 22 | MIL-T-16286 CL. E |
| Main Bank | 2" | .134" | 34 | MIL-T-16286 CL. A* |
| Main Bank | 1" | .085" | 2808 | MIL-T-16286 CL. A* |
| Economizer | 2" | .180" | 182 | MIL-T-16286 CL. A |
| Desuperheater (in Water Drum) | 2" | .220" | 6 | SA-268 TP-430 |
| Downcomers | 8 5/8" | .483" | 1 | Schedule 80 Pipe<br>ASME SA-106-B |
| Downcomers | 10 3/4" | .519" | 5 | Schedule 80 Pipe<br>ASME SA-106-B |
| Downcomers | 12 3/4" | .601 | 2 | Schedule 80 Pipe<br>ASME SA-106-B |
| Risers | 6" | .500" | 7 | ASME SA-106-B |

*These tubes may be MIL-T-16286, Class A (Seamless) or MIL-T-17188 (Seamed) electric resistance welded.

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